DESIGN AND PERFORMANCE OF HEXAGONAL FLIGHTED-TROMMELS FOR SIZE CLASSIFICATION OF BLACK PEPPER

Thesis submitted to

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of

Doctor of Philosophy

by

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under the guidance of

Prof. K. P. Pandey

DEPARTMENT OF AGRICULTURAL AND FOOD ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KHARAGPUR

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CERTIFICATE OF APPROVAL

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This is to certify that the thesis entitled **'Design and Performance of Hexagonal Flighted-Trommels for Size Classification of Black Pepper'**, submitted by **Jippu Jacob** to Indian Institute of Technology, Kharagpur, is a record of *bona fide* research work under my supervision and is worthy of consideration for the award of the degree of Doctor of Philosophy of the Institute.

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JIPPU JACOB

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LIST OF SYMBOLS AND ABBREVIATIONS

%	per cent
(-)	dimensionless unit
θ_r	angle of rolling friction, °
θ_s	angle of sliding friction, °
ω	angular velocity of screen at the particle position, rad/s
(°)	degree
/	per, or
α	trommel inclination from horizontal, degree.
A	ampere
a_0	regression constant
a_1, a_2, etc.	regression coefficient
Anon.	Anonymous
ANOVA	Analysis of variance
ASTA	American Spices Trade Association
BC	Before Christ
b_i	interval between adjacent perforations, mm
C_i	clogging index, %
cm	centimetre
C_o	correction factor for non-ideality of a hexagonal trommel in screening oversize material
C_u	correction factor for non-ideality of a hexagonal trommel in screening undersize materials
D	diameter of screen at the particle position, m
d.b.	dry basis
d_a, d_b	diameter of aperture, mm
D_c	largest diameter of hexagonal screen, m
dc	direct current
df	degree of freedom
D_i	mean base diameter of pile, cm
Eqn.	Equation
Eqns.	Equations
et al.	and others
F_C	fraction of oversize berries in feed
Fig.	Figure
Figs.	Figures

F_T	feed rate, or total feed rate of material, kg/h
F_U	feed rate of undersize material, kg/h
g	acceleration due to gravity, cm/s^2
g	gram
h	hour
ha	hectare
h_i	maximum height of pile, cm
H_m	mixture hold-up by weight for $F_T = F_O + F_U$, but for no undersize material hold-up, kg
H_{ma}	actual mixture hold-up by weight for $F_T = F_O + F_U$, kg
H_o	material hold-up by weight for $F_T = F_O$, kg
H_{oa}	actual material hold-up by weight for $F_T = F_O$, kg
hp	horsepower
Hz	heartz
i.e.	that is
IIT	Indian Institute of Technology
kg	kilogram
kW	kilowatt
L	length of trommel, m
L	litre
LSD	least significant difference
m	mass of particle, g
m	metre
min	minute
mm	millimetre
MSS	Mean sum of square
N	trommel speed, r/min
n_a	total number of apertures on screen surface
n_c	number of apertures remaining clogged at any instant
N_{cr}	critical speed of trommel, r/min
No.	number
Nos.	numbers
O_{fr}	oscillation frequency, Hz
p	pitch, mm
P_i	input power, W
P_o	output power, W
r	revolution
Rs	Indian Rupees

s	second
S.D.	Standard deviation
S_i	screening inaccuracy, %
S_{ia}	percentage by weight of undersize material in tailings, %
S_{ise}	screening inaccuracy predicted by semi-empirical model, %
Sl.	Serial
S_{PU}	percentage of undersize material screened through apertures, %
S_{RU}	screening rate of undersize material passing through apertures, kg/h
SS	Sum of square
t	duration of screening, s
T	metric tonne
T_r, T_R	mean residence time of particle, s
T_s	screening duration, s
V	volt
viz.	viza vis, like
V_{max}	limiting relative velocity of grain, cm/s
V_{pa}	particle velocity in axial direction, m/s
W	watt
w.b.	wet basis
W_d	weight of dry sample, g
W_{FU}	weight of undersize material fed to the screen in time t, kg
W_{OT}	weight of oversize material in tailings, kg
W_{SU}	weight of undersize material passing through apertures in time t, kg
W_T	total weight of tailings, kg
W_w	weight of wet sample, g
X_p	distance advanced axially by a particle in one cascade cycle of 180°

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ABSTRACT

This study mainly aimed to find an alternative to the equipments, in use for size classifying black pepper. A manually-operated flat tray sieve was evaluated by screening black pepper to reduce the content of fines in the tailings to 20, 15, 10, and 5 per cent. The output, when reducing screening inaccuracy to five per cent, was 18.2 kg per man-h, and the unit cost of sieving, Rs 1.38 per kilogram of black pepper. This projected the low capacity and high unit cost of this method. The evaluation conducted on an oscillating flat screen, for four screening durations at two feed compositions, three oscillation frequencies, and three feed rates, gave its lowest level of screening inaccuracy as 15.6 per cent only. It confirmed that this screen was incapable of providing the desired low level of screening inaccuracy of five per cent. Clogging was also seen to be cumulative and severe. Another investigation conducted with an experimental set-up comprising three hexagonal trommels having six internal flights studied the effects of feed composition (0.150, 0.325, 0.500, 0.675), feed rate (60, 90, 120, 150 kg/h), and trommel speed (10, 15, 20, 25 r/min) on screening inaccuracy, zone-wise screening percentage of fines, clogging index, and power requirement. It showed that higher feed compositions, and lower feed rates and trommel speeds were necessary for obtaining lower screening inaccuracies. Screening inaccuracies below five per cent could be achieved with the hexagonal flighted-trommels generally at a feed rate of 90 kg/h and trommel speed, 15 r/min, when the feed composition was 0.675. The highest zone-wise screening percentage occurred in the first 15-cm zone from the inlet. Clogging was seen to be not a major problem; the clogging index being only in the range 0.02-0.25 % because of the self-cleaning characteristics of the trommels. Power requirement was also found to be of a very low order (0.7-1.1 W) when producing screening inaccuracies of 5 per cent and below. The unit cost of sieving was Rs. 0.40 per kilogram of black pepper at the feed rate, 90 kg/h. Semi-empirical and empirical models developed could predict screening inaccuracy of a hexagonal flighted-trommel in terms of feed composition, feed rate, and trommel speed. The investigation showed that the hexagonal flighted-trommel was an effective alternative to the existing equipments for meeting the specific requirement of purity in grade.

Key words: Trommel, Hexagonal trommel, Trommel screen, Flighted-trommel, Hexagonal flighted-trommel, Black pepper, Size classification, Size grading, Sizing, Screening, Sieving, Grading, Screening accuracy, Screening inaccuracy, Clogging, Clogging index, Oscillating screen, Mechanical separation.

Chapter 1

INTRODUCTION

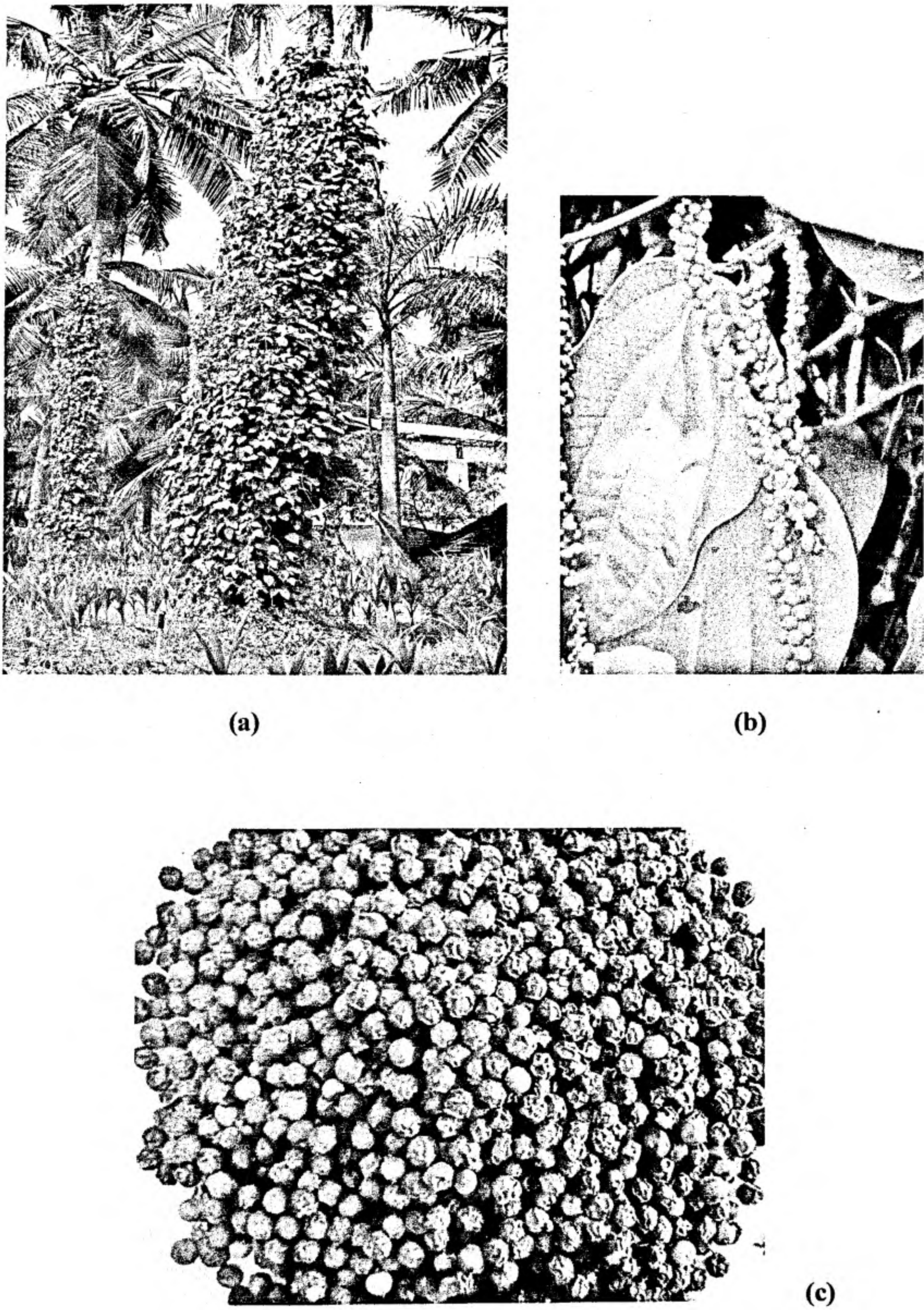
Spices, from time immemorial, are commodities of international trade. Spice trade, along with the silk trade, is perhaps the oldest international trade that inspired expeditions, wars, and colonialism. India is known to be in the international trade of spices since 4000 BC. The trade which developed initially with the Egypt and some Arabian countries was later oriented towards the West subsequent to the discovery of a sea route to India round the Cape of Good Hope by the European explorers.

The rich and diverse climatic conditions prevailing in India provide just the right environment for the cultivation of most of the spices. Hence, India is known the world over as the Land of Spices (Peter *et al.*, 2006). No country grows as many kinds of spices as India do. Among the spices, black pepper (*Piper nigrum* Linn.) is the most sought-after spice in the world. It occupies an important position in terms of the quantity traded and the value realised. According to Christopher Morley, black pepper is the *King of Spices* and cardamom the *Queen of Spices* (George, 1989).

Black pepper is the dried mature-berries of the perennial evergreen-vine, *Piper nigrum* Linn., belonging to the Piperaceae family. It is dark brown to pitch black and nearly globular with a wrinkled surface, the deep wrinkles forming a network on the dried berry (Fig. 1.1). It is valued for its culinary, medicinal, aromatic, and cosmetic properties.

Black pepper is believed to have originated in the Western Ghats in the southern part of India (Sivaraman *et al.*, 2002). Hence, India is one of its major producers. The other major producers are Indonesia, Malaysia, Sri Lanka, Vietnam, China, and Brazil. The annual world production of black pepper during 1999-2003 was between 225,680 and 342,625 metric tonnes from an area ranging from 433,693 to 583,897 ha respectively (Premaja and Manojkumar, 2007). India's contribution is estimated to be between 18 to 36 per cent of the world production.

Kerala, Karnataka, and Tamil Nadu are the States leading in the cultivation of this crop in India. The southern-most Indian State, Kerala, accounts for about 96 per cent of the



(a) (b) (c)

Fig.1.1 The black pepper – ***from the plant to the produce***

(a) - the vine trained on a coconut palm
(b) - the mature spikelets of berries on the vine
(c) - the black pepper

production in India. The official estimates of area under pepper cultivation, production, and quantity exported, in recent years, are furnished in Table 1.1.

Table 1.1 Area under cultivation and production of black pepper in India (Premaja and Manojkumar, 2007)

Year	Area, ha	Production, T
2000-'01	213,870	63,670
2001-'02	219,380	62,440
2002-'03	225,330	72,460
2003-'04	233,410	73,220
2004-'05	257,020	79,640

In the international market, around 250,000 metric tonnes of black pepper is traded annually, with USA leading the list of importing countries followed by various Republics of the erstwhile USSR, Germany, United Kingdom, Italy, and France.

India is annually earning substantial foreign exchange through the export of spices, especially black pepper (Table 1.2).

Table 1.2 Export of spices from India (Premaja and Manojkumar, 2007)

Year	Item	Quantity (T)	Value (Rs in million)
2001-'02	All spices[1]	243,200	19405.5
	Black pepper[2]	22,877	2036.9
2002-'03	All spices[1]	264,110	20867.1
	Black pepper[2]	21,609	1788.8
2003-'04	All spices[1]	254,380	19116.0
	Black pepper[2]	16,635	1427.7
2004-'05	All spices[1]	335,490	22000.0
	Black pepper[2]	14,150	1214.0
2005-'06	All spices[1]	320,530	22952.5
	Black pepper[2]	16,700 (E)	1405.0 (E)

[1] *Inclusive of black pepper* [2] *Black pepper alone* (E) *Estimated*

The different forms in which black pepper is exported are bold pepper berries, light pepper berries, pinheads, pepper powder, dehydrated green pepper, pepper in brine, frozen pepper, and white pepper. In the international markets, many types and grades of black pepper, each with specific name and quality, are recognised. The Indian pepper called *Malabar black pepper* is popular in the international markets. According to George (1989) the specific grade, *Tellicherry Garbled Extra Bold*, from India fetched the highest price due to its large size, high quality, and preference over the rest for use in the *Salami* and steak preparations in Italy. Eapen (1989) asserted that the bolder Indian grades, like *Tellicherry Garbled Special Extra Bold*, and *Tellicherry Garbled Extra Bold*, had strong market preference, particularly in the Middle East. He pointed out that this specific requirement of the market was not being met with effectively and exhorted for improved grade recovery. The situation is not much different even today.

Considering the various needs of buyers and importing countries, standard grades are prescribed by the Agricultural Marketing Adviser to the Government of India under the provisions of the Agricultural Produce (Grading and Marking) Act 1937. Under this Act, the Pepper Grading and Marking Rules 1969, prescribe grade designations and definitions of the quality of *Tellicherry Garbled Black Pepper;* and are given in Table 1.3. These are known as *Agmark* grades.

Table 1.3. Agmark Grade Specifications of black pepper (Anonymous, 1995)

Grade Designation	Size* (diameter of apertures of the sieve on which retained) (mm)	Moisture Content (maximum) (%)
TGSEB	4.75	11.5
TGEB	4.25	11.5
TG	4.25 (50 % minimum) 4.00 (50 % maximum)	11.5

* Tolerance allowed for next lower-size black pepper berries: 5 %

TGSEB Tellicherry Garbled Special Extra Bold
TGEB Tellicherry Garbled Extra Bold
TG Tellicherry Garbled

According to these, the maximum tolerance allowed for the black pepper of lower sizes in the various grades is very small. Non-adherence to these quality standards, particularly in the international trade, results in either detention of the commodity by the buyers, or its rejection, besides fetching lower price. More importantly, it adversely affects the reputation of the country. The dominant factors deciding the quantities of black pepper shipped to any given market in the world are price, quality, and ready availability. Use of efficient low-cost and high-capacity equipment in grading lowers unit cost, and ensures quality and ready availability of the product in large quantities in a shorter time. This enhances the volume of trade and thereby, the valuable foreign exchange earnings.

Size classifying of black pepper is at present carried out by sieving or screening in oscillating flat tray sieves of different sizes. Some of the disadvantages of oscillating flat tray sieves are: cumulative clogging of perforations, necessity of high-frequency low-amplitude oscillating mechanism, requirement of heavier machine components, more power requirement, high cost, and the presence of large quantities of undersize black pepper in each grade. It is also known that the oscillatory motion suitable for accurate sizing results in rapid clogging of the screen. Conversely, the oscillatory motion that prevents clogging results in low passage-rate of *fines*. In sieving, ***fines** are the particles, which can be sifted through the perforations*; in other words, the *undersize particles*.

Past studies confirmed that cumulative clogging is a major problem in the oscillating flat screens (English, 1974; Feller, 1980). Due to this, fewer perforations are available for the passage of fines. So, more fines flow into the tailing outlet and remain in the *tailings*. In screening, ***tailings** are the particles that do not pass through the perforations and, hence, collected or discharged from the upper surface of the screen, and may contain some fines if the screening is inaccurate*. This inaccuracy of a screen is known also as ***screening inaccuracy*** and is expressed as *the percentage by weight of undersize material in the total tailings*. Due to the high screening inaccuracies, the black pepper processing industries in India too are facing the problem of having more of fines in the tailings. It is at present overcome, generally, by stopping the screen at certain intervals and manually tapping off the particles that are clogging the apertures. But, this leads to frequent interruptions in the process. In certain cases, special devices like brushes or sweeps are attached to the oscillating screens for removing, at regular intervals, the particles lodged in the perforations. *Another method is the use of screens having apertures of diameter larger than the designated diameter*. For the designated aperture diameters of 4.00, 4.25, and 4.75 mm, they use even perforations of diameters 4.25, 4.50, and 5.00 mm respectively. Obviously, this results in the recovery loss of actual oversize particles. So, farmers and traders trade with lesser quantity of higher-grade material and earn less. Also, the country looses substantial foreign exchange.

The sieves operated manually are batch type and hence, the output is low. As a thumb-rule, it is taken in the industries as 15-20 kg/man-hour, when higher accuracy is insisted upon. In this case too, the aperture diameter is sometimes maintained larger than the designated diameter as mentioned earlier.

Badger and Banchero (1982), Bosoi *et al.* (1990), and Visvanathan *et al.* (1994) have reported on the use of *trommels* in screening. A **trommel** is a **revolving drum or cylindrical sieve for cleaning or sizing materials.** *In an inclined hexagonal trommel having internal flights or lifters, the solids are fed to the trommel at its upper end. As the trommel rotates, the flights located at its six corners and extending lengthwise of the drum lift and cascade the particles. The cascading particles form sheets or curtains below the flights while traversing axial to the drum. The particles progress inside the drum through a succession of cascade cycles; each cycle moving the particles one increment along the drum length. The value of this increment is dependent on the design and operating parameters of the drum. In this process, the undersize particles get sifted through the apertures and the oversize particles get discharged at the lower end.* The process of sorting using trommels was seen to be better than that on screening trays. The screen motion appeared more conducive for particle passage. Further, it also assisted in destabilising a particle clogging the screen and making it fall off its seat in the aperture during the rotation of the trommel; *i.e.*, when the relative positions of the particle and the aperture were interchanged. When an oversize particle is in its natural rest-position inside a trommel, the aperture is below the particle. But, as this particle is carried upward by the rotation of the trommel element, they gradually interchange their positions. This forces the particle to fall down from its seat due to the force of gravity and clear the aperture, provided no other force restrains it from falling down. So, clogging is reduced. Cashewnut processing industries and stone crushing industries are using trommels for sorting the materials into grades of different sizes. But, the trommels are yet to assert its place in the size classification of black pepper.

Preliminary studies showed that the hexagonal flighted-trommel was capable of ensuring more accurate sizing. It indicated also that clogging was not cumulative. But, the available literature showed no evidence of any systematic study on size classifying of black pepper in hexagonal trommels having flights. These necessitated the present investigation. Further, the parameters like trommel speed, feed rate, and feed composition were included in the study because of their certain influence on the performance of hexagonal flighted-trommels. Besides, semi-empirical and empirical models for predicting, with reasonable accuracy, the screening inaccuracy of hexagonal flighted-trommels were also considered important as it allowed a comparison of the two and then selecting the best. Such a model is useful to the designers and users of such trommels. In view of the above, and more particularly to improve the recovery of higher-grade black pepper, the present investigation was undertaken with the following major objectives:

1. **to evaluate the existing methods of size classifying black pepper in India,**
2. **to develop a reliable semi-empirical model for predicting screening inaccuracy of a hexagonal flighted-trommel in size classifying black pepper,**
3. **to investigate the effect of trommel speed, feed rate, and feed composition on screening performance of a hexagonal flighted-trommel in size classifying black pepper and assess the trommel's economic viability in that process, and**
4. **to develop a reliable empirical model for predicting screening inaccuracy of a hexagonal flighted-trommel in size classifying black pepper.**

For achieving the objectives, a manually-operated flat tray sieve and a mechanically-oscillated flat tray sieve; both in current use, were evaluated. A semi-empirical model was developed, for predicting screening inaccuracy, based on the hold-up of undersize and oversize materials in the hexagonal flighted-trommel. Three hexagonal-type trommels of aperture diameters: 4.00, 4.25, and 4.75 mm and having six internal flights were fabricated and studied at four different levels of the aforesaid parameters to determine their effect on screen performance and assess its economic viability. An empirical model was also developed, based on the experimental results, to predict screening inaccuracy of the hexagonal flighted-trommels. It was seen from the results of this investigation that the use of a hexagonal flighted-trommel in size classifying the black pepper offers many advantages.

Chapter 2

REVIEW OF LITERATURE

This chapter reports of the relevant aspects of the earlier studies reviewed and considered while formulating the present investigation. The methodologies adopted have also been to some extent founded on these past works of other investigators. The matter in this chapter is presented under the following major heads.

2.1 Spices and condiments
2.2 Black pepper
2.3 Existing methods of size classifying
2.4 Mechanical separation
2.5 Screening equipment

2.1 Spices and Condiments

Spices and condiments are in use from time immemorial. Nambiar (2002) broadly classified spices and condiments into six groups, based upon the part of the plant to which they belonged; namely, (i) rhizomes and root spices, (ii) bark spices, (iii) leaf spices, (iv) flower spices, (v) fruit spices, and (v) seed spices. Black pepper is considered both a fruit spice and a seed spice. The whole black pepper is a berry or a fruit containing a seed, whereas the white pepper is only a seed since its outer fruit portion is removed. More and more area is being brought under the cultivation of spices mainly because of their economic importance. Spices are basically high-value crops. As shown in Table 1.2 the total value being realised from the export of spices is, in general, appreciably enhancing year after year. Among the spices, black pepper is one of the most important and earliest-known spice crops.

2.2 Black Pepper

It is a plant of the humid tropics and deemed native to the rainforest of south-west coast of India. It grows abundantly in the Western Ghats and throughout the State of Kerala in India. A brief account of this plant and its produce is presented in Sections 2.2.1 through

2.2.4. It is based on the relevant portions extracted from the reports of Pruthi (1993), Nambiar (2002), Sivaraman *et al.* (2002), and Sheela (2007).

2.2.1 General botanical aspects

Black pepper (*Piper nigrum* Linn.) is a perennial, evergreen, and climbing vine belonging to the *Piperaceae* family (Fig. 1.1 a). The stem is generally swollen at the nodes. Numerous adventitious roots, known as climbing roots, are given out from the nodes. It is by these roots that the plant attaches itself to a standard and climbs up. The stem or the vine is broadly classified into: (i) terminal stem, (ii) stolons or runners, and (iii) lateral branches. The stem and branches bear alternate, shiny, dark-green, and ovate leaves. Branches emerge from the dorsal buds. Each bud is accompanied by a single leaf. The receme develops on the current year's flush opposite a leaf. Flowers are small and whitish, and borne on hanging catkins or spikes. Mature spikes, 5-30 cm long, support 30-150 flowers. Its fruits are numerous small and indehiscent berries; dull green when immature, and turning pale yellow, orange, and finally red as it ripens. These berries are arranged longitudinally on the spikes in several weak spirals (Fig. 1.1 b). It takes nearly 6-8 months from flowering to harvesting.

2.2.2 Varieties

There are many varieties of cultivated black pepper. They differ mainly in the time taken to mature, length of the spike, and size and arrangement of the berries. Each regional tract has its own selection of popular varieties, known by different vernacular names, such as *Balankotta, Karimunda, Kalluvalli, Cheriakodi, Perumkodi, Doddiga*, etc., as in Kerala, and Karnataka. The varieties, *Panniyur-1* to *Panniyur-7*, are hybrids giving 3-4 times the yield of local varieties.

2.2.3 Harvesting and curing

The produce, *black pepper*, is prepared mostly from fully matured and developed green berries by drying. Ordinarily, harvesting is by nipping the spikes by hand when the berries are about to ripen. The spikes are spread on either floor or bamboo mat and the berries are separated from the catkin by hand or trampling. Mechanical threshers are also being used. It is then dried in the sun for 4-7 days until the outer skin shrinks and turns black or dark brown (Fig. 1.1 c). In drying, the moisture content reduces from about 70 per cent to a safe moisture level below 12 per cent. The yield of dried black pepper is around 36 kg from 100 kg of fresh green berries. The average productivity of black pepper in India was 310 kg/ha in 2004-'05.

2.2.4 Uses

Black pepper is used for a variety of purposes. It is most widely used in whole or ground form for flavouring and seasoning food. It increases the shelf life of some food preparations. In Indian cuisine, it is a *must* commodity and is used in practically all types of curries. In Western cuisine, black pepper is used in clear soups, cream cheese dips, most of the savoury dishes, and in some cakes and biscuits. Its stimulating action on digestive system increases secretion of saliva and gastric juices. A decoction of pepper and dried ginger subsides fever and relieves influenza. In various skin diseases with itching, external application of black pepper with milk is prescribed. In cosmetic applications, it helps to cure acne, activates blood circulation, and stimulates the follicles. It is used also as an astringent and a toner.

2.2.5 Trading

Black pepper is traded in both ungarbled and garbled forms in the local markets. Garbling separates bold black pepper berries from pinheads, chaff, filth, etc. In the international markets, it is traded in only the garbled form unless there is a specific requirement for the ungarbled material. Garbled pepper fetches a higher price than the ungarbled. According to Mathew (2008), the prices of garbled and ungarbled black pepper were respectively Rs 143/- and Rs 137/- per kilogram on April 25, 2008.

Garbled black pepper is marketed in different trade and grade names, such as *Malabar Garbled*, *Tellicherry Garbled*, etc., as mentioned in Chapter 1. As given by the *Agmark* grade specifications, the *Tellicherry Garbled Black Pepper* is to be classified into three grades according to the size. The three grades correspond to the bold black pepper berries retained on sieves having circular apertures of diameters 4.75, 4.25, and 4.00 mm respectively (Anon., 1995; Zachariah, 2002). The tolerance allowed for the next lower size in these is only 5 per cent. However, many local traders are not insistent about this limit for the garbled material traded in the local market. Many of them allow up to 10 per cent. Therefore, two limits are to be taken care of when size classifying black pepper into *Tellicherry Garbled Black Pepper*. The above close grade-specifications almost agree with the statement of Feller *et al.* (1986) that the requirements for accurate sizing in agriculture are generally greater than the standards accepted for chemicals, ores, etc., and that the size groups and grades of agricultural products are often defined in a very narrow range - sometimes as small as 10 per cent of the product average size.

2.3 Existing Methods of Size Classifying

The *Agmark* grade specifications require that black pepper be sorted on sieves having circular apertures of the designated diameters. A survey was conducted among the black pepper traders and exporters in the port city of Kochi in Kerala to collect information on the methods being adopted for size classification. Kochi is a major centre for trading and exporting of black pepper. None of the traders and exporters except seven granted the permission to study their installations. Five were small-scale traders and the rest large-scale traders. Even those who granted the permission did so under certain conditions, for the sake of trade secrecy. Restrictions were imposed on taking certain measurements. From whatever had been permitted, it revealed that only two methods were adopted for size classifying black pepper. These were sieving on manually-operated flat sieves, and screening on mechanical oscillating flat screens. Also, this was confirmed by both the Export Inspection Agency under the Government of India, and the Spices Board, Kochi.

Further, five of the traders replied in affirmative to a query whether they used apertures of a diameter larger than the designated size on their screens. But, none except two revealed the size being used. As indicated by them, the sizes were 5.00, 4.50, and 4.25 mm for the designated diameters of 4.75, 4.25, and 4.00 mm respectively. Feller *et al.* (1986) too has pointed to the use of oversize apertures. He cited of using 10.5-mm apertures instead of 10-mm size for separating seeds smaller than 10 mm. He noted that the passage of particles lower than 10 mm was still poorer and the total passage was only 53 per cent. Though this method aids in considerably enhancing the capacity, it leads to also lower percentage of recovery of actual oversize material in each grade. Therefore, this method results in losses in terms of quantity recovered and money realised. Anyway, of the two existing methods of size classifying, traders were of the opinion that manual sieving gave better screening accuracy though at reduced output.

2.3.1 Manual sieving

Manual sieving is a batch process performed with a flat screen having numerous apertures of the same diameter. All those who were surveyed had manually-operated flat screens on their premises. Large-scale traders never used it frequently. It was mostly for screening the material that got spilled over in conveying, filling, etc. The flat screens surveyed were about 1.0 m long and 0.6 m wide. It had four handles; two each on opposite ends (Fig. 2.1). Two persons held it by these handles and the screen was shaken after loading about 2 kg of black pepper. Shaking continued for 60-150 s depending upon the accuracy desired. According to the traders, the output from manual sieving was very low if higher accuracy was insisted upon. They took 15-20 kg/man-h, as a thumb rule, for a screening inaccuracy below five percent.

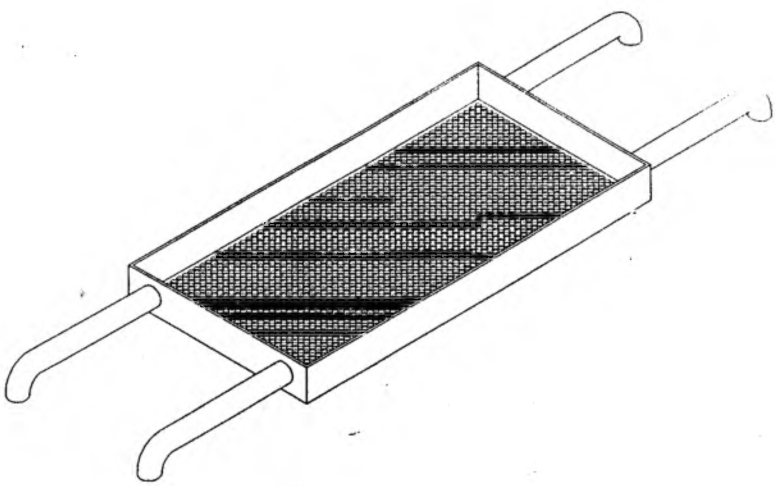


Fig. 2.1 Flat tray sieve : *manually-operated*

Further, manual sieving is costlier in Kerala because of the existing higher wage rates of Rs 200/man-day. This reflects upon the pepper price tremendously because Kerala is the State producing about 96 per cent of the black pepper in India. Besides, according to the Export Inspection Agency, a large number of small-scale traders and exporters are adopting manual sieving.

2.3.2 Mechanical sieving

Among those who were surveyed, the two large-scale traders and three small-scale traders used mechanically oscillated flat screens (Figs. 2.2 and 2.3).

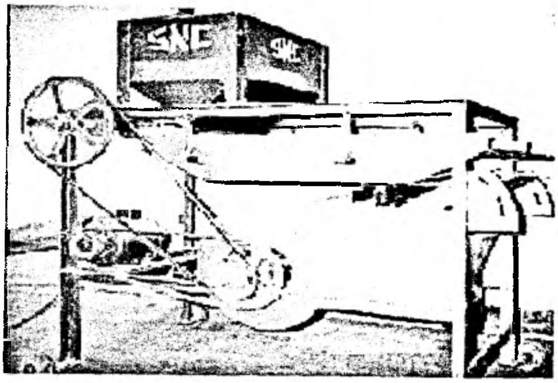


Fig. 2.2 Oscillating flat screen

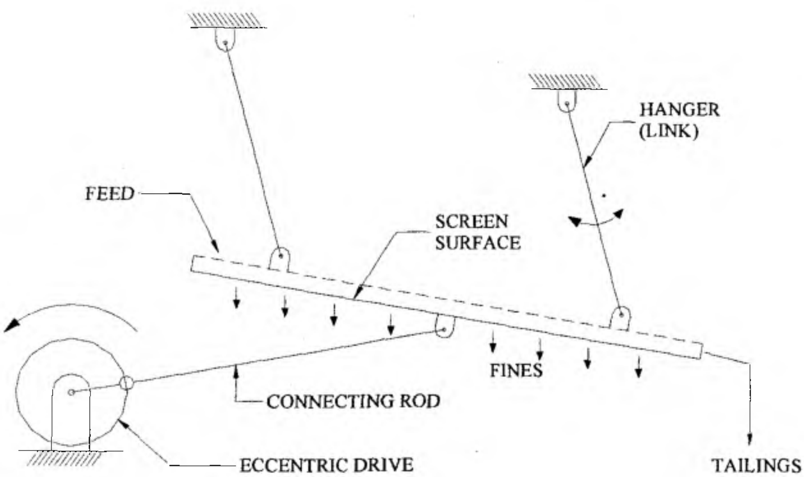


Fig. 2.3 Schematic of an oscillating flat screen

Rated output of the screens was 0.25-3.0 T/h. All, except two, were multi-deck screens; the upper deck having a screen of the largest-diameter aperture and the bottom deck the lowest diameter. High-capacity screens had three decks whereas the medium-capacity screens two decks. Screen length varied from 0.9 to 2.1 m and the width 0.6-1.0 m. All of them agreed that screening inaccuracy was higher for oscillating flat screens. One trader allowed his mechanically oscillated single-deck screen and manually-operated flat tray sieve to be used for evaluation, but without permitting prolonged testing and any alteration to the system. Based on the above, a search for an alternative to the existing methods was felt needed. The literature surveyed guided further to the present study. Some of the useful observations of the earlier researchers are presented below.

2.4 Mechanical Separation

Particle classification or separation is an important unit operation in agricultural processing. According to McCabe *et al.* (1993) separations are classified under two groups. Separations involving mass transfer between phases are known as diffusional operations, and those leading to separation of different classes of materials in a heterogeneous mixture on the basis of size, shape, and density as mechanical separations. Operations involving separation of liquid drop from gas, solids from gas, solids from liquid, and solids from solids come under mechanical separations. In general, these are carried out by the process of sedimentation or by the use of a sieve, septum, or membrane, as in a screen or a filter, which retains one component and allows the other to pass through the openings or apertures in it. The process is called sieving when a sieve is used for the separation. *In the case of black pepper, the aim is to separate solids from solids by sieving.*

2.4.1 Sieving or screening

The two terms *sieving* and *screening* are used, in general, without distinction for denoting the process of separation on the basis of size. Toledo (1994) stated that sieving is a mechanical separation process for separating fines from larger particles and for removing large solid particles from liquid streams. Henri and Vadim (2004) stated about particle classification as the division of a particle flow according to size into two or more outlet streams; coarse- and fine-flows. McCabe *et al.* (1993) defined screening as a method of separating particles according to size alone. Perry *et al.* (1987) described screening as the separation of a mixture of various sizes of grains into two or more portions by means of a screening surface; the screening surface acting as a multiple go and no-go gauge; and the final portions consisting of grains of more uniform size than those of the original mixture. By drawing a distinction between sieving and screening, Rose (1977) called mechanical separation of materials in small batches as sieving, and a continuous process as screening. *The two terms are, however, used without distinction in this thesis.*

In screening, a heterogeneous mixture is dropped on or thrown against a screening surface. The materials passing through the screen openings are called by different names such as *minus materials*, *undersize materials*, or *fines*, and those retained on a given screening surface or that do not pass through the apertures are *plus materials*, *oversize materials*, *tailings* or *tails*. All the terms except *minus materials* and *plus materials* are used in this thesis. Similarly, the terms, *near-mesh* or *near-size* particle, are used to indicate a particle whose second dimension or width is very close to that of the relevant aperture size. It can be on either side of the aperture size.

According to McCabe *et al.* (1993) a single screen divides the material into two fractions; both called *unsized fractions* because although either the upper or the lower limit of the particle sizes each fraction contains is known, the other limit is unknown. The materials passing through one screen and retained on a subsequent screen are the *intermediate materials* or *sized fraction.* The maximum and minimum particle sizes of this fraction are known. In respect of the black pepper grades, *Tellicherry Garbled Special Extra Bold*, and *Tellicherry Garbled Extra Bold*, screening aims to obtain *unsized fractions*, whereas it is *sized fraction* for the *Tellicherry Garbled.*

The main objective of screening is accurate separation by size. Its another aim includes achieving this separation at a high throughput capacity. But, according to Turnquist and Porterfield (1967), one characteristic which appeared to them to be present in all systems designed and constructed for the size classification of granular particles was that *optimum capacity and optimum size differentiation cannot be obtained simultaneously.* To achieve a high level of one, requires that less stringent specifications be applied to the other. This is true even now. However, the vast researches conducted over this period on screen surfaces, screen shapes, screen motions, etc., have made things better. As stated by Meyer *et al.* (2007), the size of particle removed during a mechanical separation process is a function of screen size, inflowing solids (quantity and type), type of separator, and flow rate over the separator. Hence, for any size grading process to be effective the screen must have the right type of screen element or screen surface.

2.4.2 Screen surface

The screen element is the component containing apertures or perforations. It is usually made of cotton, silk or synthetic fabric, metal wire, metal sheet, or metal rods or bars. The openings or apertures on it may be square, rectangular, triangular, circular or any other shape. Aperture or perforation size is specified by the minimum clear space between the two diametrically opposite edges of an opening and is usually expressed in inches or millimetres. As per *Agmark* Grade Specifications, size grading of black pepper requires that it be classified on metal screens having circular apertures of diameters, 4.75, 4.25, and 4.00 mm. The size of openings on a surface is generally uniform. Screens used in black pepper grading were seen to be using only one-size holes on a screen.

The empirical relationship given by Bosoi *et al.* (1990) is used in determining the interval between two adjacent holes from the aperture diameter. Pitch or the centre to centre distance between adjacent holes for a screen can be, then, found out from this. Description of this is given in Section 3.1.1. This method was adopted for obtaining the minimum value of pitch for the screen to be used in this study. It now requires that the screen element be used on appropriate screening equipment to achieve a good separation. The literature reviewed showed that different types of screening equipments are in use.

2.5 Screening Equipment

The device used in screening or sieving is known as a screen or sieve. Screens are generally classified in the following ways (Henderson and Perry, 1976; Badger and Banchero, 1982; Perry *et al.*, 1987; Coulson and Richardson, 1989; Bosoi *et al.*, 1990; McCabe *et al.*, 1993; Toledo, 1994; Perry and Green, 1998; Luckie, 2003).

I. According to shape
   - i. Flat Screen
   - ii. Drum screen or Trommel
     - a. Cylindrical trommel
     - b. Hexagonal trommel

II. According to screen surface
   - i. Wire screen
   - ii. Woven cloth screen
   - iii. Perforated metal screen
   - iv. Bar or rod screen

III. According to nature of screen motion

i. Stationary screen
ii. Rotary or revolving screen
iii. Oscillatory screen
iv. Vibratory screen
v. Gyratory screen

It requires that the screen surface, otherwise called screen element, of all the screens except stationary screens be imparted one or a combination of types of motion. Feller *et al.* (1986) cited that the four main functions of screen motion were to:

a) facilitate passage of particles through the screen apertures,
b) prevent the clogging of screen by oversize particles by lodging in the apertures,
c) continuously convey the particles along the screen surface, and
d) to allow each particle to reach the screen surface by mixing with the particle layers and/or by facilitating downward penetration of small particles between the larger ones (*i.e.*, trickle stratification).

Depending upon size, capacity, and type of motion, these screens are operated manually or mechanically. The screen surface may be held horizontal or inclined. In most cases, the particles pass through the apertures due to gravity. In few cases these may be forced through by a brush or centrifugal force. The type used now in size grading of black pepper is a flat metal screen with perforated surface and oscillated manually or mechanically. In order to grade the material into sized fractions, two or more screen elements, each having holes of a different size, are stacked one above the other or placed end to end. These are multi-deck screens. Black pepper traders use multi-deck screens also. In the case of drum screens, these can be also arranged concentrically to obtain sized fractions (Badger and Banchero, 1982). Single screen element having holes of different sizes also helps in getting sized fractions. Since oscillating flat screens are more in use in black pepper processing, attention is now confined to the various aspects of these.

2.5.1 Oscillating flat screen

Feller *et al.* (1986) defined that oscillating screen is essentially a perforated surface supported by parallel links and activated by an eccentric drive (Figs. 2.2 and 2.3). Oscillations are provided for the reasons cited in Section 2.5.

2.5.1.1 Screen and particle motion

Berry (1959) investigated into the basic theory of an oscillating conveyor of the form in which the vertical acceleration was limited to a value less than that due to gravity. In this, the conveyor operated without loss of contact with the material. He showed that the forward motion of material on such a conveyor proceeded by a process known as stick-slip or by continuous slipping throughout the cycle. Many researchers studying on oscillating sieves also indicated of this type of motion on screen surface. Hann and Gentry (1970) reported of the various particle motions as: (i) riding and sliding, (ii) continuous sliding, (iii) rolling with and without sliding, and (iv) hopping. These motions are not only a function of the screen motion but also a function of the particle shape. The first two are not applicable to spheres. So, the motions relevant to the black pepper, because of its high sphericity, are the last two. To impart these motions, the screen is oscillated. In some cases, it is held slightly inclined too.

It is well known that, *in screening, some of the undersize particles do not pass through the perforations. This is regarded as the* ***inaccuracy*** *of the process.* Garvie (1966) explained this phenomenon as the tendency of the particles to *skip over perforations* at high relative velocities. This shows that the relative velocity of particles in a screen must be limited to such values that it not only ensures particle passage but also its quicker passage. This is needed for lesser screening inaccuracy and higher capacity.

Kanafojski and Karwowski (1976) gave a treatise on screen motion parameters for two particle positions relative to the screen, viz., (i) in contact with the screen surface, and (ii) tossed-up in air. Hosking (1964) showed that amplitude and frequency of vibration, particularly at higher limits, exerted considerable effect on the performance of a vibratory screen. Feller and Foux (1975) obtained an empirical expression for the effect of the oscillating screen motion variables on the passage of particles through a perforation independently of the screening duration effect. They showed that the kinetic passage conditions depended on the peak screen acceleration as a major parameter, with an adjustment to screen amplitude by a correction factor. According to them the screen inclination and the linkage angle did not affect the kinetic passage conditions at values common to oscillating screens. Feller *et al.* (1986) too showed that passage percentage increased with the screen acceleration up to a maximum, and then decreased steeply at higher values of acceleration. Harrison and Blecha (1983) noted that the average velocity of a particle per cycle increased down the screen from zero for the first few cycles but became constant by about the fifth cycle. According to their findings the maximum particle velocity, without constant acceleration down the screen, was approximately the maximum screen velocity. They mentioned also that there existed many different combinations of frequency, amplitude, and screen angle, which could provide the same particle velocity. Zion *et al.*, (1992) demonstrated how the screen parameters (geometry, masses, and rotational speed), and static and dynamic particle frictions influenced relative velocity between particle and screen, direction of motion, path length, and residence time on the screen. In spite of the many attempts to improve screening accuracy by adjusting and readjusting the machine parameters and particle motions after determining the beneficial or most beneficial values for these, oscillating screens still continue to be less accurate. Khan and Shahi (2006) reported of obtaining only 69 per cent for the manual grader and 72 per cent for the motor-operated grader as separation efficiency in grading walnuts. The very fact that traders are using, even now, apertures having larger than the designated size is also an indication of the oscillating screen's lesser accuracy. Besides, if a comparison is made with a rotary screen of the same screen area, the oscillating screen with its eccentric drive is considered more complicated, noisy, and vibratory; heavier and hence expensive; and more power-demanding. The motion of a well-designed rotary screen is smoother, more balanced, and less power-demanding.

Henderson and Newman (1972) observed that the orientation of an oblong or a prolate particle was in accordance with the frequency of oscillation and its geometry. They stated that when the oscillating frequency of a pan exceeded the natural rocking frequency of a prolate particle, it would orientate itself with its major axis parallel to the plane of oscillation, and when this was less than the natural rocking frequency, it would orientate itself with its major axis perpendicular to the plane of oscillation. This is important because the orientation of the particle at the time of entry into a hole decides whether it can become successful in passing through the aperture. Bosoi *et al.* (1990) suggested that the grain pile also must be tossed up with the translatory motion to enable the elongated grains to orient themselves with their longer axis perpendicular to the sieve surface so as to facilitate their passage through the holes. As stated by McCabe *et al.* (1993), a particle would have the greatest chance of passing through the screen if it struck the surface perpendicularly, and if it were oriented with its minimum dimensions parallel to the screen surface. This is true of the black pepper too because it is its second dimension; i.e., width; which requires to be scanned in the aperture. Hence, one of the considerations in selecting the present study was to allow the berries a vertical fall through a longer distance. This would enable them to orient themselves in such a way as to enter the aperture with its major or longer axis perpendicular to the plane of the aperture opening. This was thought to improve the probability of passage.

In an oscillating screen, a particle gets conveyed about the screen's surface, due to the screen and particle motions, and at an appropriate opportunity enters an aperture to pass through it, get trapped in it, jump out of it, or be driven out of it. If the particle remains trapped in it, that aperture becomes unavailable for further screening. Then, the aperture is considered as clogged.

2.5.1.2 Clogging

Clogging or blinding of screen continues to be a major problem with the oscillating sieves even now. It is considered cumulative too because more and more apertures become clogged with the passage of screening time. A number of researchers identified clogging as one of the major reasons for the higher screening inaccuracies and lower screening capacities of oscillating screens.

Fink (1958) reported about 50 years ago that clogging decreased sizing accuracy. Rose and English (1973), as far as is known, gave the first mathematical treatment of sieving on the basis of the controlling role of blinding. However, they did not study the diffusion of the blinding material out of the sieve cloth. They showed that, for accurate sieve analyses, it was essential that the amount of material upon the sieve be maintained less than a limiting amount. By developing this further, English (1974) evaluated the effect of accumulative clogging on screen capacity. Feller and Foux (1976) used passage rate factors to calculate sizing efficiency as a function of time but only for conditions that clogging does not occur. Continuing this work, Feller (1977) determined clogging rate factor as the ratio between the rate of clogging with particles of various sizes during a certain period and the quantity of free particles of these sizes on the screen. Rose (1977) showed that a sieving process can be defined in terms of three parameters, each of which are analogous to a diffusion coefficient; one for the diffusion of blinding material into the sieve cloth, another for the diffusion of this material out of the sieve cloth, and another for the diffusion of undersize material through the sieve cloth. But, this was for a screen made of cloth. Feller (1980), in a study on screening analysis, after considering both passage and clogging, defined screening rate function as the sum of the passage and clogging rate factors versus relative particle size. It is stated to be a continuous decreasing function since the probability for a particle to enter a perforation decreased as the particle size increased. Apling (1984) showed that oversize particles of sizes very close to the apertures blinded the screen more.

In spite of a number of studies being conducted on clogging, its elimination or near-elimination continues to be elusive. Except for a method developed by Feller *et al.* (1986), rest of the methods continues to be the earlier ones.

2.5.1.3 Clearing of clogged apertures

One method to release the trapped particle is to increase screen acceleration. But, that leads to reduced passage rates of undersize particles through the apertures. Therefore, *the screen motion which reduces clogging hinders particle passage, and which improves particle passage causes clogging; both leading to screening inaccuracy.*

Bosoi *et al.* (1990) proved that the necessary condition for a particle, having a diameter close to that of the aperture, to jump out of the opening of a horizontal sieve was when its acceleration was infinity. This is impossible in practice. Hence, self-cleaning cannot be ensured in horizontal sieves by increasing acceleration. However, in an inclined sieve, self-cleaning is attainable by increasing acceleration many times greater than that normally used. But, increased acceleration hinders particle passage through the apertures. So, the release of some particles much larger than the aperture size is effected by operating the screen at higher accelerations either continuously, or intermittently for a certain period at predetermined intervals.

Some other methods are also adopted for releasing the particles remaining trapped in the apertures. An old method is to stop the screen at some intervals and manually dislodge the particles by tapping the screen element from below. This leads to interruptions in the process and demands constant attention of an operator. As reported by Feller *et al.* (1986) another method was the use of brushes or rollers that moved back and forth beneath the screen surface to dislodge the particles. The operation of a machine having all these additions becomes more complicated and expensive. According to them, the method most commonly used was to incorporate rubber balls that jumped in cages below the screen and randomly hit the bottom of screen element. This tended to release the particles in the upward direction. The balls were agitated by the screen oscillations itself. Therefore, it became inefficient at the low accelerations required for accurate sizing.

In a study, Feller *et al.* (1986) concluded that (i) the optimum acceleration given to a screen for high passage rate of near-size particles through the apertures increased both the quantity and size range of the particles that remain trapped in the apertures, (ii) the trapped particles must be got released from the apertures as often as every few seconds for obtaining accurate sizing, (iii) vertical motion was the most appropriate for releasing the trapped particles by inertia force, and (iv) a screen with two simultaneous motions; one ideal for particle passage and another adequate for frequent release of the trapped particles; gave nearly perfect sizing without cumulative clogging. They considered this a significant improvement in sizing over conventional screening. A limitation, according to them, was the reduction in material mixing because of low screen acceleration, which necessitated the feeding of material in a thin layer. Its operation is likely to be noisier and may demand more power. It may also require heavier sections for its components to withstand the impact force exerted on them.

However, in an approximate comparison, revolving screens are considered more advantageous for reduction in clogging because of its self-cleaning characteristic. As it revolves, the particle trapped in the aperture is taken upwards. As it reaches the top, the particle has more chances for getting released from the edges of the aperture under its own weight provided the moments due to frictional forces are not greater. An exploratory study at the beginning of this study also indicated this. Besides, in a rotary screen, it is possible to dispense with the reciprocating motions proposed by Feller *et al.* (1986).

2.5.2 Trommel

Among the screening equipment cited in Section 2.5, one is a drum screen or trommel. Coulson and Richardson (1989) defined that *a trommel consisted of a slowly rotating perforated cylinder with its axis at a slight angle to the horizontal.* The material fed at the upper end gradually move down the screen and pass over the apertures with the result that the fines get one or more opportunities to pass through the apertures. The oversize particles, together with any undersize particle that failed in passing through the apertures, get discharged at the lower end. Badger and Banchero (1982) gave four different arrangements of trommels (Fig. 2.4 a through d). All are used for obtaining *sized fractions*. Hence, the tailings or the fines, as the case may be, are successively screened.

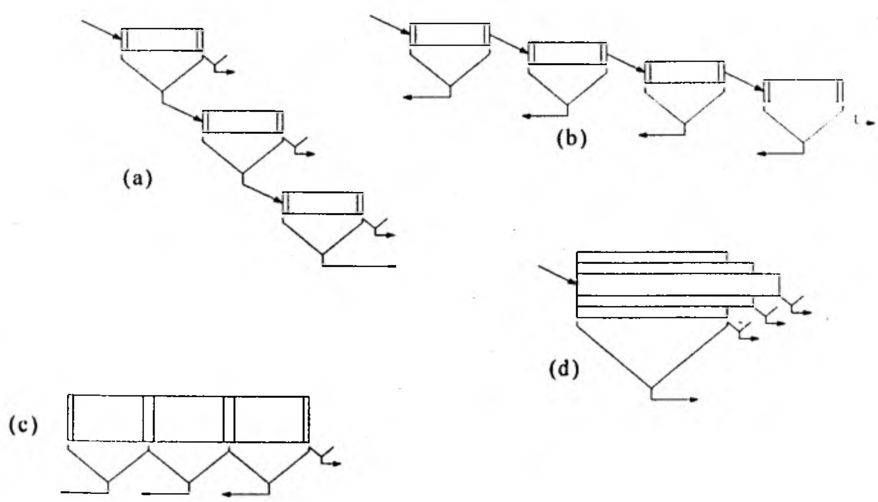


Fig. 2.4 Trommel arrangements

(a) One-size screen on each trommel ; coarsest trommel first
(b) One-size screen on each trommel ; finest trommel first
(c) Different-size screens on one trommel
(d) Different-size screens on concentric trommels

(Badger and Banchero, 1982)

In arrangement (a), the first has the largest apertures and the last the smallest (Fig. 2.4 a). The trommels are arranged mostly one below the other, but slightly staggered to one end. In arrangement (b), the case is reverse for the aperture sizes, and the trommels stand arranged mostly end to end; obviously at slightly different levels (Fig. 2.4 b). Still another variation is a single trommel with the finest perforations at the feed end and the coarsest at the discharge end (Fig. 2.4 c). Separate collectors are placed for each zone of one-size apertures. The arrangement (d) consists of several concentric trommels (Fig. 2.4 d). The innermost is the longest and possesses the coarsest apertures. This arrangement is, however, more complicated.

Bosoi *et* al. (1990) tried three methods in a trommel with a view to increase its speed for higher screening capacities. It was by placing respectively a sliding board alone, a sliding board and a curved plate, and finally a sliding board, a grain stripper, a brush, and a plane stationary plate in the cylinder. They considered all the three to be effective, especially the third one, in spite of a separation efficiency of only 70 per cent. But, it appears to have been at a high speed of rotation. Perry *et al.* (1987) reported that revolving screens or trommel screens, once widely used, were getting replaced by vibrating screens. According to them, capacities of trommels were not great and efficiency relatively low. Their observation can be true of cylindrical sieves without flights or lifters. But, for trommels having a hexagonal cross-section and having lifters, it may not be true of screening accuracy. Further, the particle and screen motions in a hexagonal trommel with flights are likely to be more favourable for particle passage and clean up of clogged holes than in an oscillating screen. The present study covered this aspect too.

Cylindrical sieves are reported to be used in combine harvesters in addition to the screening trays (Kanafojski and Karwowski, 1976). The cylindrical surface was made of turns of wire of diameter 3.0-3.5 mm. The wire was wound in a helical manner such that slits of specified width were formed in between the adjacent turns. But, the sorting is on the basis of the least dimension, *i.e.*, thickness, of the particle. Black pepper, on the other hand, is to be sorted by its second dimension, which is the width.

Narvankar et al. (2005) developed a rotating screen grader. But, it is for orchard crops and hence cannot be as such applied for sorting black pepper. Visvanathan *et al.* (1994)

developed a trommel type cleaner-*cum*-grader for *sesame* seed. It cleaned and graded the seeds into two grades. It was 150 cm long and 36 cm in diameter. The sieve was divided into three zones along the length; each of 50-cm length. Aperture diameter, though uniform in a zone, was different for the three zones. So, it was of the type shown by Badger and Banchero (1982) and given in Fig. 2.4 c. But, it was operated by hand at 30-35 r/min. Its effectiveness was only 70.5 per cent. Among the reasons for its low effectiveness, one might be the absence of flights in the drum, and yet another it's cylindrical shape instead of a hexagonal shape. Material is not adequately dispersed in a rotating drum without flights. In addition, those who used cylindrical sieves seem to have overlooked the fact that in fabricating a cylindrical drum the plate containing circular holes is provided a curvilinear bend. This leads to distortion of the holes' edges and results in reducing the effective diameter in the direction of bend. Therefore, those undersize particles, which are near-size, are not allowed to pass through. This results in more undersize materials in tailings. This lacuna can be overcome by providing a hexagonal shape to the transverse cross-section of the trommel.

Survey of the literature revealed that not much work has been reported on the performance of trommels. Such reports are found to be few and far between. At the same time, trommels were known to be in use in cashewnut grading, stone grading, etc. Likewise, rotating cylindrical drums having internal lifting flights or lifters were in common use in chemical and metallurgical industries. Exploratory studies indicated that certain similarities existed between these drums and the hexagonal trommels having flights. Hence, the review was extended to these drums too.

2.5.2.1 Particle movement in a trommel with flights

The rotating drums used in chemical and metallurgical industries are for unit operations like mixing, drying, etc. Axes of these drums remain generally tilted from the horizontal by a small angle. A report indicated that these drums were popular whenever a large throughput was required (Sherritt *et al.*, 1993). They also noted that these drums were preferred for their *ease of operation*. The movement of solids through a rotating drum is reported as a complex process involving the interplay between the *transverse* mixing of solids together with an *axial* velocity component; both leading to *cascading* of the particles (Saeman, 1951; Perron and Bui, 1992; Lebas *et al.*, 1995; Loni and Sai, 2004). As pointed out, internal flights aided in dispersing the material over the cross-section of drum. In such a drum, the flow of particle occurred in *two phases*. The *airborne phase* consisted of the falling particles, which are displaced axially due to slope of the drum. The *dense phase* consisted of the particles, which rested on the bed at the bottom of drum or the flights. Axial displacement of the particles in the dense phase occurred by bouncing, rolling, and sliding due to the drum inclination and/or inter-particle collisions. The particles interchanged freely between the two phases. Tilt angle of the axis of drum is generally in the range 1-6^0. Its rotational speed was also low.

Most of these are applicable to also the hexagonal flighted-trommels, but only with some modifications due to certain apparent differences between the two. Importantly, difference exists in their cross-sectional shape and size. Whereas one is cylindrical and large, the other hexagonal and small. One is perforated whereas the other unperforated. The method adopted in Section 3.3 for the calculation of theoretical residence time and material hold-up in the hexagonal trommel is basically that of these drums. The residence time and the material hold-up in a trommel are dependent on trommel speed, feed rate, screen inclination, feed composition, etc. These have to be properly selected. Similarly, the effectiveness of separation of solids by a trommel can be affected by many different variables. Four among them are (i) trommel speed, (ii) feed rate, (iii) feed composition, and (iv) aperture size. Present study covers basically these. Trommel inclination, though a factor, was however kept constant.

2.5.2.2 Trommel speed

As reported by Perry and Green (1998), trommels stood operated at the low speeds of 15-20 r/min. Berlage *et al.* (1984) tried speeds of 10, 15, 20, and 25 r/min in his indent cylinder for cleaning, and separating *alfalfa* seeds and *pigweed* seeds. Maximum purity was achieved at the lowest speed. Visvanathan *et al.* (1994) used 30-35 r/min for the trommel used for grading and cleaning sesame seed. It gave an effectiveness of only 70.5 per cent. It could have probably given a higher effectiveness at a lower speed. Further, centrifugal force on the particle must not be allowed to dominate over particle mass.

Besides, trommel speed has to be selected based on the circumferential velocity required by the particles to pass through the apertures easily.

2.5.2.3 Feed rate

Rose (1977) indicated that the time to pass fines in an oscillating screen can increase rapidly with increasing load on the sieve. It was further revealed that at very small feed rates the behaviour was anomalous. This was because the screen deck oscillated in a way different from that, which occurred at high feed rates. The result pointed to the necessity of limiting the amount of material upon the sieve. Fowler and Lim (1959) found that high effectiveness of separation of finely divided solid on a vibrating screen was dependent on the selection of proper combinations of feed rate and screen aperture as main variables with a control of the angle of inclination and frequency of vibration as the main interaction. It was reported that all things being constant the effectiveness of separation increased with a decrease in the feed. Feller *et al.* (1986) also suggested to feed the material in a thin layer in the screen developed by them. In the hexagonal flighted-trommel also, this is true because the screen area available to the particles at any instant is small. Therefore, the load on the screen has to be properly selected.

2.5.2.4 Feed composition

Standish and Meta (1985) supplied to a vibrating screen the feed from a mass flow feed bin and the flow rate adjusted by means of a slide gate at the bottom of bin. Test mixtures were prepared by mixing stock material of different size fractions by hand into a homogenous mixture. The effect of *oversize particles* was found to be beneficial in speeding up the screening of near-mesh material. Standish *et al.* (1986) studied the efficiency of screening sinter particles and coke particles in a vibratory screen for a range of operating variables which included flow rate, deck angle, speed, *oversize in feed,* and mesh size. The preparation of feed stock and its mode of feeding into the screen in the present study were based on these studies.

2.5.2.5 Aperture size

Fowler and Lim (1959) indicated that separation effectiveness increased with aperture size. They subjected apertures of sizes 60, 50, 40, and 30 meshes to the investigation. The aperture diameters selected in the present study were, however, 4.00, 4.25, and 4.75 mm because of the reasons stated earlier. Further, these diameters were in agreement with the observation of Luckie (2003) that the size of the materials fed to a screen deck should not be greater than two or four times the aperture size.

2.5.2.6 Trommel inclination

In their study on continuous screening, Standish and Meta (1985) fixed the oscillating screen at an angle of 11.5^0. This value represented the mid-range of the variable considered for the experiment. But, in another study, Standish *et al.* (1986) used deck angles of 11.5, 12.5, and 14.5^0. The cleaner-*cum*-grader of Visvanathan *et al.* (1994) appears to have been operated with its axis horizontal. In this study, after a preliminary investigation, the angle was kept constant at 4^0.

The review of literature was extended also to other types of classifiers like probability screening machine, roller-gap classifier, classifier using imaging, etc. to verify their suitability for black pepper grading. They are presented below.

2.5.3 Probability screening machine

Beeckmans *et al.* (1985) studied the performance characteristics of a probability-screening machine. As described, a multiple-deck probability-screening machine was a device having relatively short and steeply inclined screens, to which vibrations were imparted predominantly in a direction normal to the plane of the screen. The principal advantages included their high throughput rate per unit area, and reduced tendency to blind. But, these advantages were to some extent offset by their incapability to give a high degree of screening accuracy. They indicated also that the screening efficiencies of conventional screening machines were never ideal even at low throughputs, and that it deteriorated with increasing throughput. Because of the low screening accuracy of this machine, it was not considered for black pepper classification.

2.5.4 Roller-gap classifier

Roller-gap *classifier* is a device that sorts particles between a pair of counter-rotating rollers with diverging axes and located in a plane slightly inclined to the horizontal

(Beeckmans and Thielen, 1986). Particles fed at the apex end, travel downhill between the rollers until the gap exceeds the least dimension of the particle, which then falls down. A series of trays are placed below the rollers depending upon the desired width of size intervals. It provides sized fractions. Though it is a rapid method, it cannot be adopted for black pepper since it is to be classified by its second dimension.

2.5.5 Gravity table sorting

Gravity tables are used in the seed industry and other industries to sort materials by physical properties including bulk density, specific gravity, and particle size (Krueger *et al.*, 2007). In sizing of granular and globular materials like black pepper where difference in the sizes between the adjacent grades is too narrow, this method is not effective. The material used in their study was commodity corn.

2.5.6 Sorting by imaging

Sorting by imaging is comparatively a newer technique. But it is expensive too. Paulus and Schrevens (1999), and Hahn and Sanchez (2000) evaluated sizes of apples and carrots respectively using imaging algorithms. Majumdar and Jayas (2000) used machine vision for the classification of cereal grains. These methods are more accurate too. But, such expensive methods cannot be adopted for size classifying black pepper in India in the near future because of the weaker economic conditions of farmers. Cheaper, but effective, mechanical size classifying equipment is the need of Indian farmers at present. This shall, besides others, enable the farmers to have these equipment serviced and repaired locally in case of breakdowns. Hexagonal flighted-trommel is an equipment that can satisfy these requirements.

Based on the above, it was considered that a hexagonal trommel having flights would be an effective alternative to the equipment now in use for sizing of black pepper in India, and that it needed a detailed systematic investigation to establish its utility for the same. Hence, this study. In the succeeding Sections of this thesis, the terms, *trommel(s)* or *hexagonal trommel(s)*, mean *hexagonal flighted-trommels* unless otherwise specified.

Chapter 3

THEORETICAL CONSIDERATIONS

This chapter deals with theoretical aspects of design and operation of the hexagonal flighted-trommels, and performance evaluation of the sieves used in the study, and further, the development of a semi-empirical model for predicting the screening inaccuracy of a hexagonal flighted-trommel. Its presentation has been organised under the following major heads.

3.1 Design and operation of a hexagonal flighted-trommel

3.2 Performance evaluation of sieves

3.3 Development of a semi-empirical model for predicting screening inaccuracy of a hexagonal flighted-trommel

3.1 Design and Operation of a Hexagonal Flighted-Trommel

A hexagonal flighted-trommel comprises mainly a screen element that is perforated, six flights or lifters, a feed hopper and its chute, a feeding mechanism, collection trays, power transmission systems, and a main frame. Design considerations of some of these components are as follows.

3.1.1 Perforated screen element

Black pepper is to be classified by screening through round apertures of diameters 4.00, 4.25, and 4.75 mm under this study. Therefore, the trommel fabricated was provided with facilities for changing the screen element based on the required size of apertures. On a perforated screen element, the round apertures, whose principal dimension is the diameter, are so located that their centres lie at the vertices of the six equilateral triangles forming a hexagon (Fig. 3.1). According to Bosoi *et al.* (1990), the apertures must be placed at such a distance from each other that the shape and dimensional accuracy are not lost during punching and the strength of the whole screen is not affected. Two terms associated with its design are *pitch* and *interval* (Fig. 3.1). The c*entre to centre distance between adjacent holes is known as the pitch* whereas the *minimum distance between edges of two adjacent holes is the interval.*

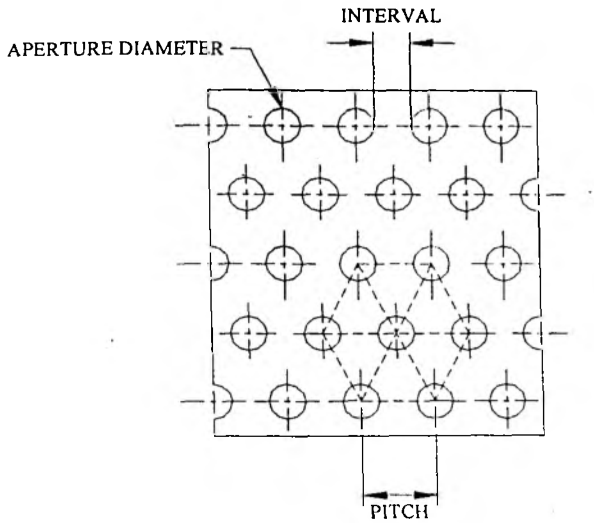


Fig. 3.1 Screen element

Bosoi *et al.* (1990) gave an empirical *relationship* between the interval and the aperture diameter as:

$$b_i = 0.9\sqrt{d_a} \qquad ...(3.1)$$

where b_i = interval between adjacent perforations, and
d_a = aperture diameter.

Accordingly, pitch, p, is given by

$$p \geq 0.9\sqrt{d_a} + d_a \qquad ...(3.2)$$

Therefore, *minimum* values of the pitch corresponding to the aperture diameters of 4.00, 4.25, and 4.75 mm are 5.80, 6.11, and 6.71 mm respectively. Considering the availability of standard sizes, 8.00 mm was selected as the pitch and made common to all the three screen elements irrespective of the aperture sizes. This made uniform the density of population of apertures on the three trommels.

3.1.2 Trommel shape and size

The most advantageous transverse cross-section for a trommel is circular since it is a rotary unit. But, projected profile of a circular aperture changes from round to an ellipse if the plate containing the aperture is provided a curvilinear bend to roll it into a cylindrical drum. In sizing black pepper, sifting has to be through round apertures whose projected profiles are circular. This requires that screening be done essentially through the apertures on a flat screen element. Therefore, the screen element was provided angular bends, instead of the curvilinear bend, to form a trommel having a hexagonal transverse cross-section. This provided six flat surfaces containing round apertures whose projected profiles remained circular itself except at the six corners of the trommel. Further, a hexagon approaches a circle more than a triangle, square, or pentagon. From the point of balancing too the former is better. Though a polygon having more than six sides approaches a circle better than a hexagon, this was not considered because of its larger number of corners where the projected profiles of round apertures remain distorted. The actual number of apertures of designated shape and size on the trommel becomes fewer if the number of corners is increased.

The cross-sectional dimensions of trommel were selected considering the peripheral/circumferential velocity to be maintained for the screen. Peripheral velocity was calculated as:

$$V_p = \frac{\pi DN}{60} \qquad \text{...(3.3)}$$

where V_p = peripheral velocity, m/s;
D = diameter of trommel, m; and
N = speed of trommel, r/min.

Further, peripheral velocity is also a factor, which controls the relative motion of particles inside a hexagonal flighted-trommel. Also, this controls the passage of particles through the screen. In the present case, values of the peripheral velocity more relevant to the study are those relating to (i) radius of hexagon; *i.e., radius of its circumcircle*, and (ii) short radius; *i.e., apotherm.* Bosoi *et al.* (1990) proposed a circumferential velocity in the range 0.65-0.75 m/s for the cylindrical screens. But, preliminary studies showed that peripheral velocities between 0.10 and 0.24 m/s provided better conditions for passage of the black pepper through the designated apertures. This necessitated the selection of radius of hexagon as 100 mm and its corresponding short radius as 87 mm for the trommel speeds maintained in the range 10-25 r/min. Accordingly, width of each side was 100 mm.

Similarly, the length of trommel was decided considering the mean residence time of the particles in the trommel and the particle velocity in the axial direction of the drum. This was determined as:

$$L = V_{pa} T_r \qquad \text{...(3.4)}$$

where L = length of trommel, m;
V_{pa} = particle velocity in axial direction, m/s; and
T_r = mean residence time of particle, s.

For the cross-sectional dimensions and the speeds selected, the length of trommel was fixed to be 100 cm. This made available an effective length of 90 cm for screening. Effective length is the actual length of the screen portion containing the apertures. The unperforated portions at both the ends accounted for the remaining 10-cm length. The effective length selected almost agreed with the suggestion of Bosoi *et al.* (1990) that the length to diameter ratio should be between 3.75 and 4.00 for cylindrical screens.

3.1.3 Critical speed

It is known that the downward release of a particle lodged at the apex of a revolving screen is dependent upon the screen velocity and the forces acting on the particles. The forces are the *force of gravity on the particle* and the *centrifugal force*. The *screen velocity, which maintains equilibrium between the two forces, when a particle is at the apex of the screen, is called critical speed.* For the particle to be in equilibrium;

$$mg = m\omega^2 \frac{D}{2} \qquad \text{...(3.5)}$$

where m = mass of particle, g;
g = acceleration due to gravity, cm/s^2;
ω = angular velocity of screen at the particle position, rad/s; and
D = diameter of screen at the particle position, m.

If peripheral velocity is considered, this gets simplified to:

$$N_{cr} = \frac{60\sqrt{g}}{\pi\sqrt{2D}} = \frac{42.3}{\sqrt{D}} \qquad \text{...(3.6)}$$

where N_{cr} = critical speed of trommel, r/min.

As is known, a trommel must be operated at a speed below the critical speed for effective screening. In this study, the speed of a point at the radius of hexagon decided the critical speed. The critical speed pertaining to a point at the radius of 10 cm was 94.6 r/min.

3.2 Performance Evaluation of Sieves

In evaluating the performance of sieves including hexagonal trommels, some important parameters were to be determined. These are described below.

3.2.1 Power requirement of a trommel

The power required by a trommel is rotary power. Shell (2003), and Avallone and Baumeister III (1997), gave an expression for rotary power as:

$$hp = \frac{2\pi NT}{60} \qquad \text{... (3.7)}$$

where hp = horsepower required, W;
N = speed of trommel, r/min; and
T = torque, N-m.

3.2.2 Screening inaccuracy

It is the percentage by weight of fines or undersize material in the tailings determined on the basis of total weight of tailings. It indicates the inaccuracy of screening and is calculated using the expression:

$$S_{ia} = \frac{(W_T - W_{OT}) \times 100}{W_T} \qquad \text{...(3.8)}$$

where S_{ia} = screening inaccuracy, %;
W_T = total weight of tailings, kg; and
W_{OT} = weight of oversize material in tailings, kg.

In this study, it is the *screening inaccuracy* that is considered instead of *screening accuracy* because, *Agmark* grades mainly specify the limit of fines in various grades.

3.2.3 Zone-wise screening percentage of fines

It indicates the *separation* effectiveness of each zone of 15-cm length of the screen with respect to the fines fed to the respective zone. It is expressed as the percentage of fines separated through the apertures of a zone of 15-cm length of the trommel for a certain time period and determined on the basis of the total weight of fines fed to that zone in that time period. It is expressed as:

$$S_{PU} = \frac{W_{SU} \times 100}{W_{FU}} \qquad \ldots(3.9)$$

where S_{PU} = zone-wise screening percentage of fines, %;
W_{SU} = weight of fines passing through apertures of a 15-cm zone in time t, kg;
W_{FU} = weight of fines fed to that zone in time t, kg; and
t = duration of screening, h.

3.2.4 Clogging index

It is the percentage of the number of apertures remaining clogged at any instant with respect to the total number of apertures on the screen element. It is given as:

$$C_i = \frac{n_c \times 100}{n_a} \qquad \ldots(3.10)$$

where C_i = clogging index, %;
n_c = number of apertures remaining clogged at any instant; and
n_a = total number of apertures on screen element.

3.3 Development of a Semi-empirical Model for Predicting Screening Inaccuracy of a Hexagonal Flighted-Trommel

Knowledge of the movement of particles in a hexagonal trommel having flights or lifters is required for a fundamental study of the screening occurring in the equipment. In Fig. 3.2 is shown a particle resting at the bottom of a hexagonal trommel having six flights such that θ = 0. On rotating the drum, the flight just behind the particle carries the particle upwards. As θ approaches 180°, the particle cascades from the flight and falls on the opposite side of hexagon. Thus, one cycle of lifting and cascading of the particle takes place during rotation of the trommel from 0° to 180°. Inclination of the drum causes the particle to land a short distance ahead of its corresponding initial position and more towards the outlet (Fig. 3.3). Next cycle of lifting and cascading takes place during the rotation from 180° to 360°. Thus, the particle progresses towards the outlet through a number of such cycles executed successively. Finally, the particle gets discharged from the trommel at its outlet.

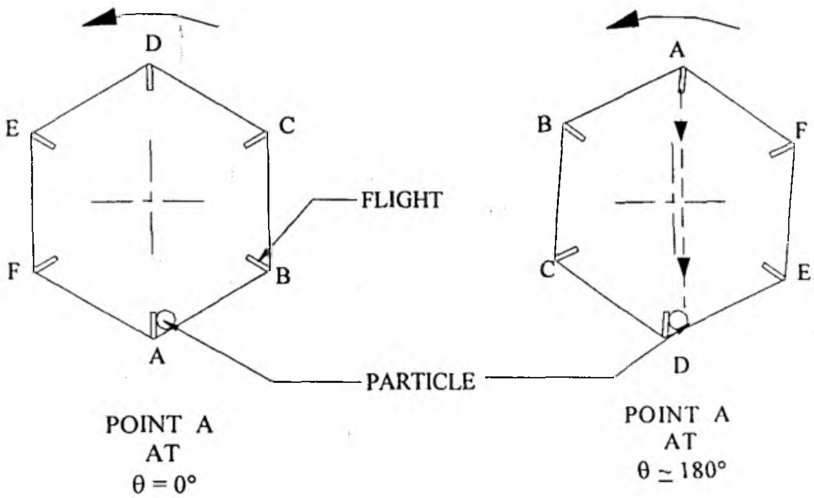


Fig. 3.2 Particle position in a trommel at two stages of trommel rotation

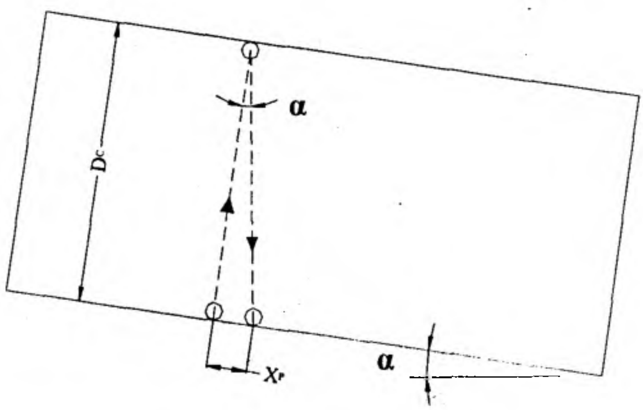


Fig. 3.3 Particle trajectory in a trommel during one half-cycle

In this study, the assumptions made are:

i) the particle possesses no relative velocity with respect to the drum during its lift,

ii) the perforations on the flight prevent the particle from rolling or sliding down the flight at angles of rolling or sliding friction,

iii) the perforations on the flights and the momentum due to rotation cause the particles to be lifted through 180° before cascading begins,

iv) the sum of all deviations of the particle from its cascade trajectory due to inter-particle collisions and bounces is zero, and

v) the particle is subjected to exactly two cycles of alternate lifting and cascading in one revolution of the drum.

Based on these assumptions, the distance advanced in the axial direction of trommel by a particle in one cascade cycle is given as:

$$X_p = D_c \tan\alpha \qquad \text{...(3.11)}$$

where X_p = distance advanced axially by a particle in one cascade cycle of 180°, m;
D_c = largest diameter of hexagonal trommel, m; and
α = trommel inclination from horizontal, degree.

Accordingly, the distance advanced in one revolution of the trommel is 2 X_p, and

$$V_{pa} = \frac{2\ X_p N}{60} \qquad \text{...(3.12)}$$

where V_{pa} = velocity of a particle in axial direction, m/s; and
N = speed of rotation of trommel, r/min.

Residence time of the particle in the trommel is then calculated from the relationship:

$$T_R = \frac{L}{V_{pa}} = \frac{60\,L}{2\,N\,D_c \tan\alpha} \qquad \text{...(3.13)}$$

where T_R = mean residence time of particle, s; and
L = length of trommel, m.

It is known that the particles, fed during this period, stay in the trommel.

Now, from material balance equation,

$$F_T = F_U + F_O \qquad \text{...(3.14)}$$

where F_T = total feed rate of material, kg/h;
F_U = feed rate of undersize material, kg/h; and
F_O = feed rate of oversize material, kg/h.

Considering that the feed is of only oversize material, the material balance equation is:

$$F_T = F_O \quad \text{...(3.15)}$$

Therefore, the material hold-up, which is the weight of particles staying in the trommel at any instant, is given by the equation:

$$H_o = \frac{F_T \ T_R}{3600} \quad \text{...(3.16)}$$

Substituting Eqn (3.13) into the above expression yields:

$$H_o = \frac{F_T}{3600} \times \frac{60L}{2ND_c \tan \alpha} \quad \text{...(3.17)}$$

where H_o = material hold-up by weight for $F_T = F_O$, kg.

However, in the actual condition, some deviation is noted in terms of material hold-up which may be due to rolling or sliding of the particles, inter-particle collisions, end conditions of the screen, or a combination of these. It may also be due to bouncing of particles upon landing at the end of a cascade. Therefore, a **correction factor** for non-ideality can be incorporated in Eqn (3.17) as:

$$H_{oa} = \frac{C_o F_T L}{120ND_c \tan \alpha} \quad \text{...(3.18)}$$

where H_{oa} = actual material hold-up by weight for F_T = FO, kg; and
Co = a correction factor for non-ideality of a hexagonal flighted-trommel in screening oversize material.

The correction factor, C_o, would be less than unity.

Now, considering that the feed is a mixture of both the undersize and the oversize materials; in an ideal situation, all the undersize particles would get sifted apertures. Hence, the material hold-up would consist of only oversize material and is given as:

$$H_m = \frac{C_o (F_T - F_U) L}{120ND_c \tan \alpha} \quad \text{...(3.19)}$$

where H_m = mixture hold-up by weight for $F_T = F_O + F_U$, but for no undersize material hold-up, kg.

But, in actual condition, some undersize particles do not pass through the apertures and these add to the material hold-up. It may be due to inter-particle collision, high relative velocity of particle, blinding of screen, and overpopulation of particles per unit area. Therefore, Eqn (3.19) is modified by incorporating a **correction factor** for non-ideality due to undersize material hold-up as:

$$H_{ma} = \frac{C_o(F_T - F_U)L}{120ND_c \tan\alpha} + \frac{C_u F_U L}{120ND_c \tan\alpha} \qquad \ldots(3.20)$$

where H_{ma} = actual mixture hold-up by weight for $F_T = F_O + F_U$, kg; and
C_u = a correction factor for non-ideality of a hexagonal flighted-trommel in screening undersize materials.

The correction factor, C_u, would be less than unity.

This hold-up material becomes the tailings in a screening operation. The amount of undersize material in this is an indication of the inaccuracy of screening. That is,

$$S_{ise} = \frac{H_{ma} - H_m}{H_{ma}} \times 100 \qquad \ldots(3.21)$$

where S_{ise} = screening inaccuracy predicted by semi-empirical model, %.

Therefore, the final expression for predicting screening inaccuracy is:

$$S_{ise} = \frac{C_u F_U \times 100}{C_o(F_T - F_U) + C_u F_U} = 100 - \frac{C_o(F_T - F_U)100}{C_o(F_T - F_U) + C_u F_U} \qquad \ldots(3.22)$$

C_o and C_u can be determined experimentally for a material-screen combination. Knowing the mean percentage of undersize material in the feed it is possible to determine the feed rate of undersize material from the total feed rate. Using these values, the screening inaccuracy can be predicted.

Based on the design procedure discussed in this chapter, a hexagonal flighted-trommel and three screen elements having apertures of diameters, 4.00, 4.25, and 4.75 mm, were designed and developed for use in the present study. The developed semi-empirical model was used for predicting the screening inaccuracy of the developed hexagonal flighted-trommel in size classification of black pepper.

Chapter 4

MATERIALS AND METHODS

This chapter deals mainly with the experiments conducted to determine the properties of black pepper, evaluate the existing methods for size classifying black pepper, study the performance of the hexagonal flighted-trommels, and determine the values of correction factors in the semi-empirical model for predicting screening inaccuracies. Descriptions of the experimental facilities and the research techniques utilised are also presented. These are organised under the following major heads.

4.1 Experiments

4.2 Experimental Set-up

4.3 Experimental Procedure and Evaluation

4.1 Experiments

The properties of agricultural produces vary widely based upon the conditions to which they are exposed. Hence, some of the properties were determined to better specify their characteristics before being used in experiments. Besides, information on some of the properties was also needed in the design and operation of trommels. So, the first set of experiments was for investigating the physical and engineering properties of black pepper. The second set was for evaluating the manually-operated sieve and the third set for the oscillating flat screen. The fourth set of experiments, designed to be conducted utilising the main experimental set-up, comprised two sets. First was for studying the effect of feed and trommel parameters on the trommel performance and its power requirement. Second was for determining values of the correction factors, C_0 and C_u, in Eqn (3.22) for predicting the screening inaccuracy. Accordingly, the experiments planned under this investigation were as given below.

4.1.1 Physical properties of black pepper

The plan of experiments drawn-up to determine the physical properties was as shown in Table 4.1 that follows.

Table 4.1 Research plan for determining physical properties

Sl. No.	Property	Quantity per Sample Lot	Sample Lots	Replications per Sample Lot	Total No of Experiments
1	Moisture content	40 g	20	5	100
2 3	Physical dimensions[1] Sphericity[1]	1 berry	20	10	200
4	Volume	100 berries	20	5	100
5 6	1000-grain weight[2] Grain weight[2]	1000 berries	20	5	100
7	Bulk density	One bucketful	20	5	100
8	Specific gravity	100 berries	20	5	100
		Grand total			700

[1] both used the same samples and observations [2] both used the same samples and observations

4.1.2 Engineering properties of black pepper

The experiments for determination of the three engineering properties were conducted according to the plan given below in Table 4.2.

Table 4.2 Research plan for determining engineering properties

Sl. No.	Property	Quantity per Sample Lot	Sample Lots	Replications per Sample Lot	Total No of Experiments
1	Angle of repose in piling	0.5 L	20	5	100
2	Coefficient of rolling friction	5 berries	40	1	40
3	Coefficient of sliding friction	3 berries	200	1	200
		Grand total			340

4.1.3 Manually-operated flat tray sieve

Black pepper weighing 2 kg was planned to be put on the sieve and shaken till the content of undersize berries in the tailings was reduced to 20, 15, 10, and 5 % with a tolerance of -2 %. These represented four among the stages through which the screening inaccuracy may pass while getting reduced to less than 5 per cent. The conduct of these experiments was for determining the output and cost of sieving. Accordingly, its research plan was as given below.

Weight of feedstock/sample	= 2 kg
Screening inaccuracy levels	= 20, 15, 10, and 5 % (tolerance: -2 %)
Dependent variables	= (i) Output (ii) Cost of sieving
Number of sample lots	= 3
Number of replications	= 6
Total number of experiments	= 18

4.1.4 Oscillating flat screen

In this study, the screening inaccuracy and clogging index were to be determined at the 60th, 80th, 100th and 120th second of starting the machine. Since the trader did not permit prolonged testing, only two levels were selected for the feed composition. Experiments on clogging were carried out separately since it required stopping of the machine intermittently. Research plans of these are given in Tables 4.3 and 4.4 respectively.

Table 4.3 Research plan for determining screening inaccuracy of an oscillating flat screen

Sl.No.	Independent Variable	Treatment Level			
1	Feed composition, (-)	0.330	0.675		
2	Feed rate, kg/h	150	250	350	
3	Frequency of oscillation, Hz	6	8	12	
4	Screening duration, s	60	80	100	120
	Dependent Variable				
1	Screening inaccuracy, %				

No. of replications = 3
No. of feedstock lot = 1
No. of treatments per feedstock lot = 72
Total no. of experiments = 216 (i.e., *with 3 replications*)

Table 4.4 Research plan for determining clogging index of an oscillating flat screen

Sl.No	Independent Variable	Treatment Level			
1	Feed composition, (-)	0.330	0.675		
2	Feed rate, kg/h	150	250	350	
3	Frequency of oscillation, Hz	6	8	12	
4	Screening duration, s	60	80	100	120
	Dependent Variable				
1	Clogging index, %				

No. of replications = 3
No. of feedstock lot = 1
No. of treatments per feedstock lot = 72
Total no. of experiments = 216 (i.e., *with 3 replications*)

4.1.5 Hexagonal flighted-trommel

Considering the influence of factors such as *feed* composition, *feed rate*, and *trommel speed* on the performance of a hexagonal flighted-trommel, a 3-factor factorial experiment in a completely randomized design was adopted in this study. The three independent variables and their levels selected are listed in Table 4.5. Besides, the list of five dependent variables is also given. The criteria adopted in selecting the various levels of independent parameters are given in Section 4.1.7.

Table 4.5 Research plan for investigating the effect of feed and trommel parameters on trommel performance

Sl. No.	Indenendent Variable	Treatment Level			
1	Feed composition (-)				
	(fraction of oversize material in feed by weight)	0.150	0.325	0.500	0.675
2	Feed rate, kg/h	60	90	120	150
3	Trommel speed, r/min	10	15	20	25
	Dependent Variable				
1	Screening inaccuracy, %				
2	Zone-wise screening percentage of fines, %				
3	Clogging index (-)				
4	Power requirement, W				

No. of replications = 6
No. of trommels = 3 (*Trommels of aperture diameters 4.00, 4.25, and 4.75 mm*)
No. of treatments per trommel = 64
No. of experiments per trommel = 384 (i.e., *with 6 replications*)
Total no. of experiments for 3 trommels = 1152

4.1.6 Correction factors, C_o and C_u, in the semi-empirical model

Material hold-ups by weight of the undersize-oversize mixture, and that of only the oversize black pepper in the hexagonal flighted-trommels were to be separately obtained for determining the values of C_o and C_u in Eqn (3.22) of the semi-empirical model. In respect of C_o, the experiments were designed as a 2-factor factorial experiment as given in Table 4.6. The variable, feed composition, was not required, since only the oversize material was being used as feedstock.

Table 4.6 Research plan for determining the correction factor, C_o

Sl.No.	Independent Variable	Treatment Level			
1	Feed rate, kg/h	60	90	120	150
2	Trommel speed, r/min	10	15	20	25
	Dependent Variable				
1	Oversize-material hold-up, kg				

No. of replications = 3 No. of trommels = 3
(*Trommels of aperture diameters 4.00, 4.25, and 4.75 mm*)
No. of treatments per trommel = 16
Total no. of experiments for 3 trommels = 144 (*i.e., with 3 replications*)

In determining the values of C_u, separate experiments were designed for the three hexagonal flighted-trommels keeping the same three independent variables and the four variable levels as in Section 4.1.5. Inclusion of the variable, feed composition, was because the feedstock required a mixture of oversize and undersize black pepper. The research plan is given in Table 4.7.

Table 4.7 Research plan for determining the correction factor, C_u

Sl.No.	Independent Variable	Treatment Level			
1	Feed composition (-)	0.150	0.325	0.500	0.675
2	Feed rate, kg/h	60	90	120	150
3	Trommel speed, r/min	10	15	20	25
	Dependent Variable				
1	Undersize-oversize-material hold-up, kg				

No. of replications = 3
No. of trommels = 3 (Trommels of aperture diameters 4.00, 4.25, and 4.75 mm)
No. of treatments per trommel = 64
Total no. of experiments for 3 trommels = 576 (i.e., with 6 replications)

4.1.7 Selection of various parameter levels of hexagonal flighted-trommels

Selection of various levels for the feed and the trommel parameters shown in Tables 4.5 through 4.7 were based on the following considerations in addition to those which have been cited earlier, especially in Sections 2.5.2.2 through 2.5.2.4 and 3.1.3.

4.1.7.1 Feed composition

Among the various factors considered, the factor related to feedstock is the feed composition. It is generally expressed in two ways.

i) As a fraction of the oversize material in the feedstock by weight.
ii) As a ratio between oversize and undersize material in the feedstock by weight.

The former was seen used by Standish and Meta (1985). So, the same was adopted in this study. Accordingly, the treatment levels were 0.150, 0.325, 0.500 and 0.675 in the case of former and approximately 0.18:1, 0.5:1, 1:1 and 2:1 in respect of the latter. The four levels of feed composition represented the four conditions, which the fresh farm-level black pepper may attain during the progress of screening from initial to final condition.

4.1.7.2 Feed rate

Preliminary studies showed that the feed rate of about 90 kg/h produced satisfactory results in a trommel of the type selected in this study. This was closely in agreement with the specific loading per unit sieve-area recommended by Klenin *et al.* (1985) for peas on a flat screen. Feed rates on either side of this were taken as the other three levels.

4.1.7.3 Trommel speed

According to Coulson and Richardson (1989), the trommel speed must be between one-third, and one-half of the critical speed. This range is 31-47 r/min for the critical speed of 94.6 r/min, which was calculated under Section 3.1.3. But, initial trials with the trommel produced very high screening inaccuracies at the above range. This may be because of the nearly-spherical shape of the black pepper. Similarly, the speeds corresponding to the peripheral velocities ranging from 0.65 to 0.75 m/s as suggested by Bosoi *et al.* (1990) was still higher than those indicated by Coulson and Richardson (1989). So, based on the preliminary studies, speeds of 10, 15, 20, and 25 r/min were selected for this study.

4.2 Experimental Set-up

The experimental facilities utilised, according to the research plan, for achieving the objectives under this study were as presented below.

4.2.1 Manually-operated flat tray sieve

The experimental set-up for evaluating the output and cost of sieving of manual sieving was an existing flat tray sieve of the following specifications.

Screen size	= 0.9 x 0.6 m
Aperture diameter	= 4.25 mm

Pitch	=	8 mm
Total number of apertures	=	9685
Frame	=	Wooden
Screen element material	=	Galvanized iron
Weight	=	2.7 kg
No. of operators required	=	2

It was relatively new and in regular use on the farm of a trader in Kochi. Two experienced labourers at the farm operated the sieve.

4.2.2 Oscillating flat screen

An existing single-deck oscillating flat screen at the premises of a trader in Kochi was used as the experimental set-up. It was evaluated for screening inaccuracy and clogging index. The specifications and operating conditions are furnished below.

Screen size	=	0.9 x 0.6 m
Aperture diameter	=	4.25 mm
Pitch	=	8 mm
Total number of apertures	=	9685
Deck inclination	=	4°
Amplitude of oscillation	=	8 mm
Frequency	=	6, 8, and 12 Hz
Feed rate	=	150, 250, and 350 kg/h
Feed composition	=	0.330 and 0.675
Motor rating	=	0.5 hp 1440 r/min
Screen element material	=	Galvanized iron

Since the trader did not permit to alter the machine, the experiments were confined to the available settings of the machine.

4.2.3 Hexagonal flighted-trommel

The main facility for the major experiments was a hexagonal flighted-trommel. It was developed with two objectives: (1) to investigate the effect of feed and trommel parameters on the screening performance of a hexagonal flighted-trommel, and (2) to determine the values of correction factors in the semi-empirical model. Its major components were: (i) hexagonal trommel element fitted with six flights, (ii) hopper and feeding mechanism, (iii) main frame, (iv) collection trays, (v) power transmission system, and (vi) power supply system. The set-up is shown in Figs. 4.1 through 4.3.

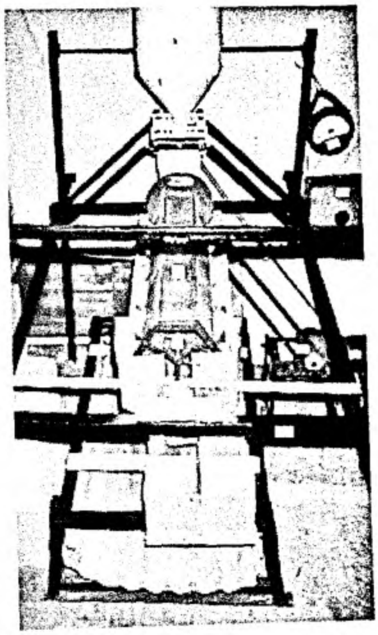


Fig. 4.1 Experimental set-up of hexagonal flighted-trommel
- a front view

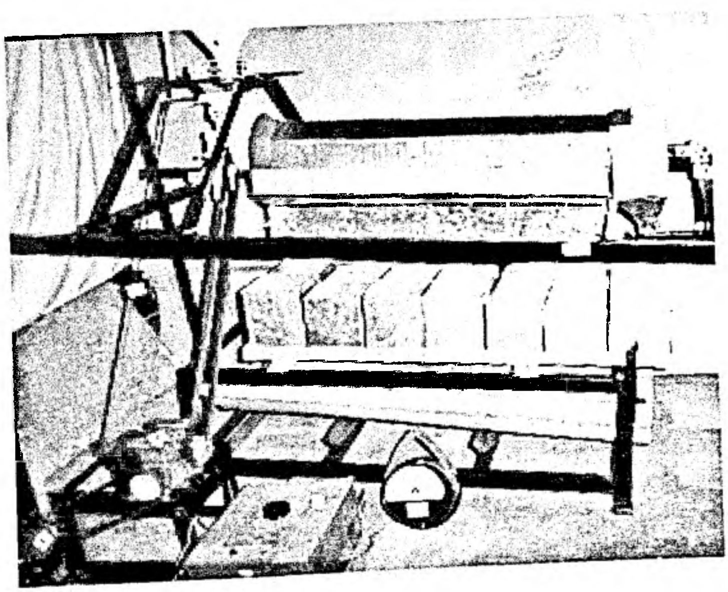


Fig. 4.2 Experimental set-up of hexagonal flighted-trommel
- a side view

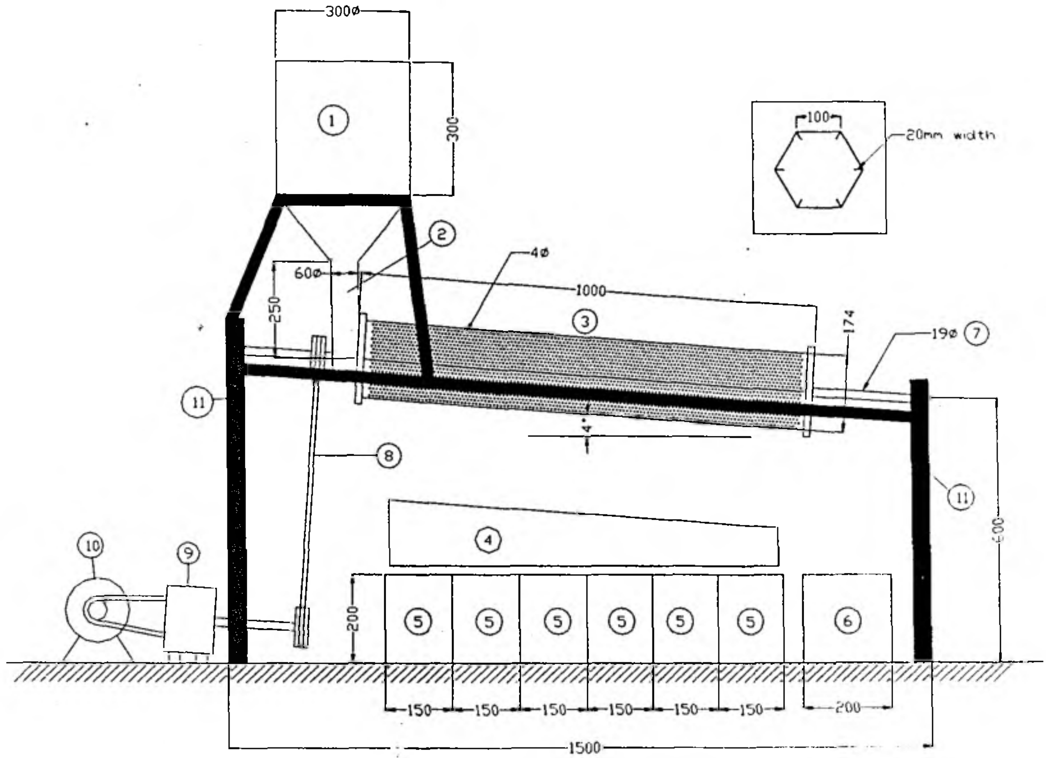


Fig. 4.3 Schematic diagram of the main experimental set-up of hexagonal flighted-trommel

1. Hopper
2. Feed chute
3. Hexagonal screen
4. Guide chute
5. Collection trays for fines
6. Collection trays for tailings
7. Trommel shaft
8. Belt drive
9. Speed reduction gearbox
10. Electric motor
11. Main frame

(Inset shows cross-sectional view of trommel and its lifting flights)

4.2.3.1 Hexagonal trommel element

Three hexagonal trommel elements were fabricated from perforated galvanized iron sheets of 22 gauge (Fig. 4.4). Diameters of the circular apertures on the three trommel elements were 4.00, 4.25, and 4.75 mm respectively. The aperture diameters selected were based on the requirement of black pepper traders and farmers. The pitch, as detailed in Section 3.1.1, was taken as 8 mm for all the three trommels. Preliminary trials showed that peripheral velocities between 0.10 and 0.24 m/s of the trommel provided better conditions for the passage of black pepper through the apertures of designated sizes. Therefore, as stated in Section 3.1.2, the radius of hexagon; *i.e., radius of circumcircle*, was selected as 100 mm and its short radius; *i.e., apotherm*, as 87 mm. Maximum peripheral velocity was encountered at the radius of 100 mm. At the radius of 100 mm and speeds of 10, 15, 20, and 25 r/min the peripheral velocities were 0.105, 0.157, 0.209 and 0.262 m/s respectively. Similarly, the radius of 87 mm provided peripheral velocities of 0.091, 0.137, 0.182 and 0.228 m/s respectively at the same trommel speeds.

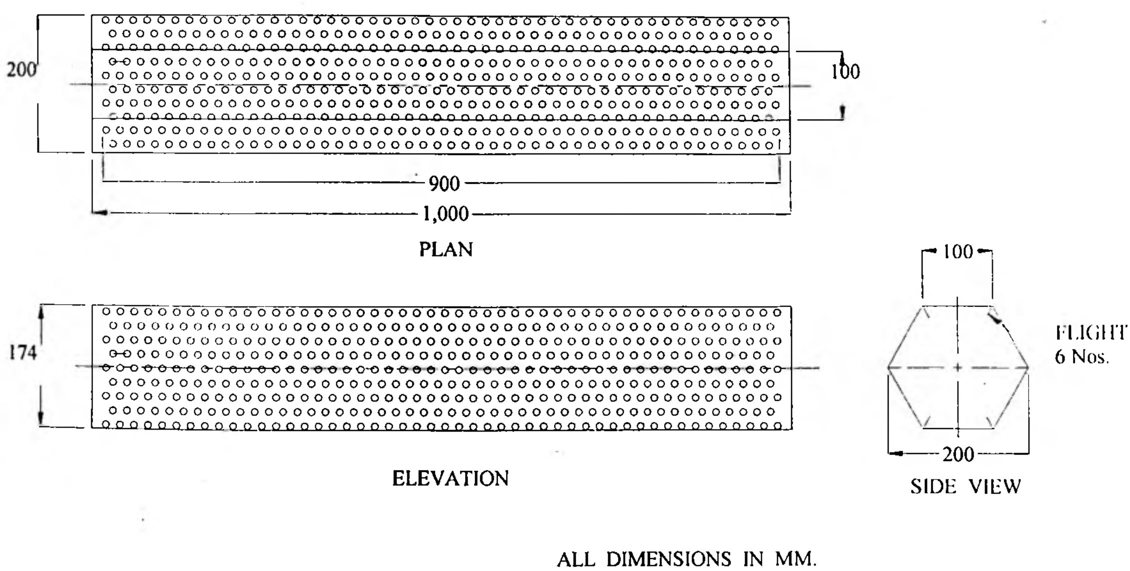


Fig. 4.4 Hexagonal trommel element

The total number of apertures on a trommel element having effective length, 90 cm, and perimeter, 60 cm, was 9685. Preliminary trials showed also that flights or lifters provided inside the trommel element at each of the six corners helped in carrying the black pepper upwards during the trommel's rotation and dropping it on to the lower flat surface of the hexagon. This helped the particles to fall into the aperture or trommel surface at a steeper angle of incidence, which created favourable conditions for the passage of particles through the apertures. Besides, it provided sliding, rolling, or both to the particles remaining in the trommel for further scanning by the apertures. Flights measuring 90 cm long and 2 cm wide were fixed at each of the six corners. Overall length of trommel element was 100 cm and each of its sides measured 10 cm. Each end of the trommel's element was mounted on a hexagonal trommel frame for which two hexagonal frames were fabricated from mild steel angle (Fig. 4.5). The hexagonal frame at the discharge end was attached through spokes to an A-class galvanized iron pipe of inner diameter 12 mm and length 1500 mm (Fig. 4.5). This pipe served as the trommel shaft. The hexagonal frame at the feed end was connected to an annular disc having outer diameter 250 mm and inner diameter 105 mm (Fig. 4.5). The annular disc was also connected to the trommel shaft through spokes. A feed chute was provided at the feed end of hexagonal flighted-trommel (Fig. 4.6). It was fabricated from a galvanized iron sheet of 2-mm thickness. The discharge end of feed chute was inserted into the trommel through the inner hole of annular disc. Therefore, the corresponding end of the trommel shaft passed through the inner hole of annular disc and the lower end of feed chute and emerged out on the outer side of feed chute. The set-up was so arranged that the components did not obstruct rotation of the shaft and facilitated unhindered flow of black pepper into the trommel without getting spilled out in transit.

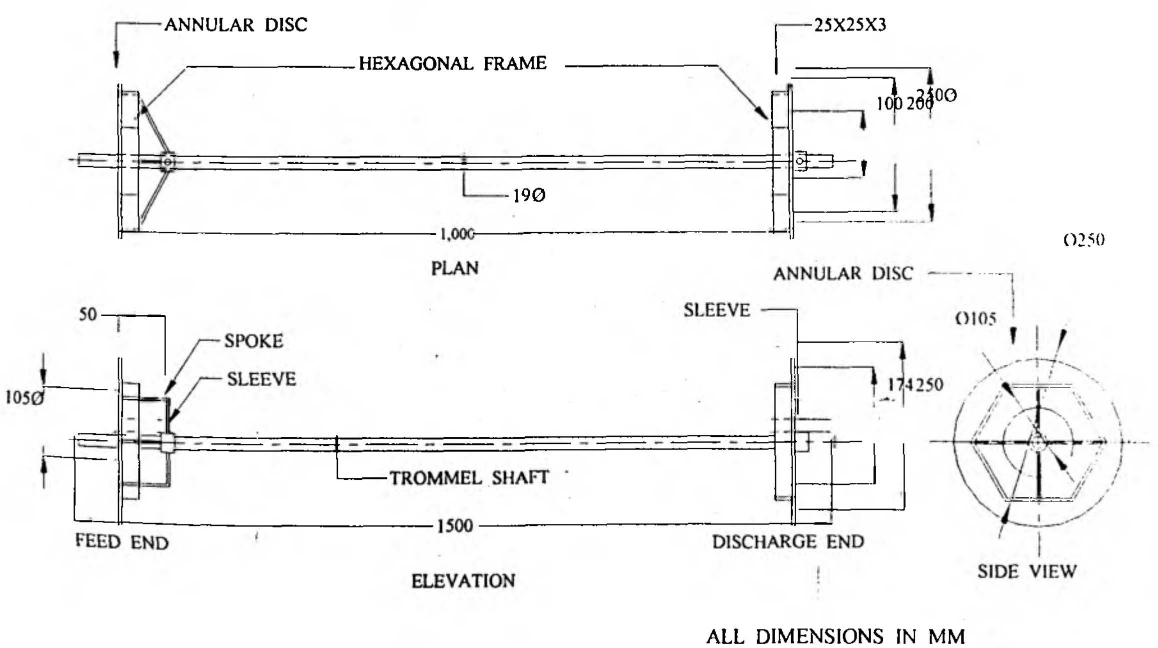


FIG. 4.5 Hexagonal frame and trommel shaft

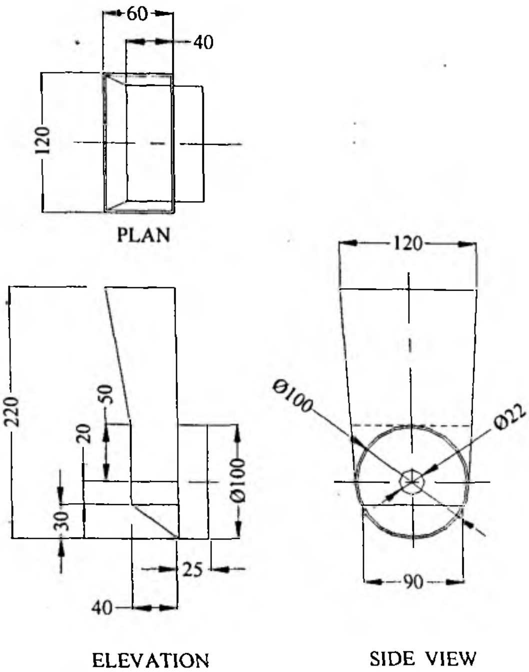


Fig. 4.6 Feed chute

4.2.3.2 Hopper and feeding mechanism

A galvanized iron hopper of capacity 0.025 m^3 was fabricated for storing the black pepper (Fig. 4.7). This could store nearly 14 kg of black pepper based on its bulk density determined in this study. The hopper bottom was provided an angle of 42° from the horizontal. This made it greater by nearly 5° than the angle of repose of black pepper, and facilitated unhindered flow of the particles. This angle was, obviously, larger than the angle of sliding friction and the angle of rolling friction. The hopper was mounted at the top end of the feed chute. A regulator gate provided at the middle of hopper tail chute aided in starting and cutting-off the flow of feed to the trommel. A 22-mm circular orifice at the bottom of tail chute served as the exit, for the feed material, from the hopper to the feed chute. But, an orifice of this diameter provided a larger feed rate than desired. At the same time, an orifice smaller than this often hindered the flow due to bridging. So, it became necessary to insert a rod into the orifice to reduce the cross-section, and simultaneously to stimulate the flow through agitation of the feed stock just above the orifice. It was found also that this rod, called regulator rod, must have different diameters because of the variations in particle sizes in each feed composition. Diameters of the rods selected based on the trials are given in Table 4.8 below.

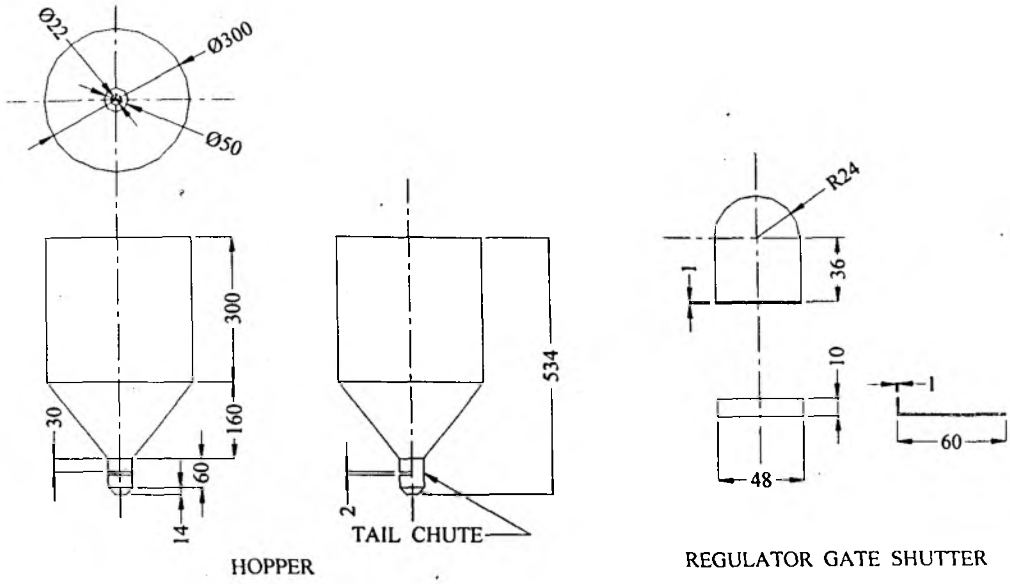


Fig. 4.7 Hopper and regulator gate shutter

Table 4.8 Regulator rod diameters for different feed rates

	Rod Diameter, mm			
Feed Rate	Feed Composition, (-)			
kg/h	0.150	0.325	0.500	0.675
60	11.2	10.6	10.3	9.9
90	6.8	6.1	5.6	5.2
120	4.9	4.5	4.1	3.9
150	3.4	3.2	3.1	3.0

These rods were free to move laterally within the orifice and hence seldom occupied the centre position of the orifice. Bottom end of the rod was modified to a mushroom head, and just placed on the surface of trommel shaft as in a cam-follower arrangement. Movement of the shaft imparted a small vibration to the rod, which in turn agitated the particles in the proximity of the rod. This prevented bridging of particles above the orifice and maintained a regular flow of material.

4.2.3.3 Main frame

The hexagonal flighted-trommel together with its shaft and bearings were fitted on the crossbars of a mild steel main frame (Figs. 4.1 through 4.3). The frame was so fabricated that it permitted changing of the angle of inclination of trommel from horizontal up to 12° in steps of 2° for facilitating explorative studies. Overall dimensions of the main frame were as follows.

Length		: 1500 mm	Width	: 900 mm
Height:	Rear end	: 750 mm	Fore end	: 600 mm

4.2.3.4 Collection trays

Aluminium boxes of 15-cm square and 20 cm height were used for collecting the fines. Six trays were placed below the trommel element; each one collecting fines falling through each 15-cm long zone. Six trays covered the entire effective length of trommel. A tray, 20 cm long, 15 cm wide, and 20 cm high, collected the tailings or overflow from the trommel. Fines passing through the apertures were guided into the trays by a guide chute placed between the trommel and the trays.

4.2.3.5 Power transmission system

A variable speed electric motor rotated the trommel shaft through a speed reduction gearbox and two sets of belt drives. The gearbox provided a speed reduction ratio of 26:1. The belt drive between motor and speed reduction gearbox provided another 4:1 ratio, thus obtaining a total reduction ratio of 104:1. The other speed reduction ratios selected for the above belt drive were 6:1, 3:1, and 2.4:1 to obtain trommel shaft speeds of 10, 20, and 25 r/min respectively at the same motor speed. The belt drive between gearbox and trommel shaft maintained a constant speed ratio of 1:1.

4.2.3.6 Prime mover (Power supply system)

A variable speed dc shunt electric motor of 0.5 hp was used to drive the trommel. The dc motor was connected to the ac supply through a controller, step-down transformer and wattmeter. The controller regulated the speed. Specifications of the motor, step-down transformer, and controller are provided in Appendix-A.

4.2.3.7 Brake dynamometer for power measurement

The hexagonal flighted-trommel was rotated through its main shaft by transmitting the rotary power from an electric motor as described in Sections 4.2.3.5 and 4.2.3.6. Shell (2003), Webster (1999), and Avallone and Baumeister III (1997), have pointed to the use of prony brake, an absorption dynamometer, for measuring rotary power. Hence, a prony brake arrangement was used in this study. The brake-arm length was 0.25 m. The outer end of brake arm rested on a load cell of capacity, 5.0 kg. The speed of shaft was measured with a digital tachometer.

4.3 Experimental Procedure and Evaluation

In this Section, the details of experiments performed according to the research plan given in Section 4.1 are presented.

4.3.1 Determination of physical properties of black pepper

A number of researchers have reported on the physical and engineering properties of agricultural materials. The treatise by Mohsenin (1980) covered almost all aspects of the properties of agricultural materials. Most of the researchers took that as the basis. It was so in this study too. In addition, the works by the following were also considered. Teckchandani (1988) studied on pigeon pea. Visvanathan *et al.* (1996) studied on the physical properties of ***neem nut***. The studies by Gupta and Das (1997), and Jain and Bal (1997) were on *sunflower seeds* and *pearl millet* respectively. Molenda *et al.* (2000) reported on the friction of wheat on corrugated and smooth galvanized iron surface. Perez *et al.* (2007) and Sirisomboon *et al.* (2007) have emphasized on the importance of physical and engineering properties of agricultural produces in the design of equipment. Based mainly on these, the methods adopted in the evaluation of the various properties of black pepper are presented below under their respective heads.

4.3.1.1 General appearance

The black pepper used in the study consisted of the commodity collected from 20 different markets in the State of Kerala in India. Because of the heterogeneity with respect to the varieties being cultivated all over the State, the black pepper traded is always not homogeneous in nature. The samples collected for experiments were also, therefore, not homogeneous. The general features of these samples were judged by visual observation for the evaluation of colour, shape, and surface characteristics.

4.3.1.2 Moisture content

Moisture content of black pepper was determined for each of the 20 lots. Five samples, each weighing 40 g, were drawn from each lot. Their moisture content was determined by distillation with toluene following Method 2 of the ASTA Analytical Methods for Moisture (Distillation Method). The moisture content was finally calculated as:

$$Moisture\ \ content,\ \%\ (w.b.) = \frac{W_m}{W_w} \times 100 \qquad ...(4.1)$$

$$Moisture\ \ content,\ \%\ (d.b.) = \frac{W_m}{W_w - W_m} \times 100 \qquad ...(4.2)$$

where W_m = weight of water collected, g; and
W_w = weight of wet sample, g.

4.3.1.3 Physical dimensions

The shape of black pepper is spherical or nearly spherical. In size classifying a nearly-spherical object, using circular aperture, sorting is on the basis of its second dimension. The measurement of physical dimensions is, therefore, important. As its size is very small, a simple technique was used to facilitate measurement of length of the following intercepts, which represent its length, width, and thickness:

i) largest intercept, (*a*);
ii) largest intercept normal to *a*, (*b*); and
iii) largest intercept normal to *a* and *b*, (*c*).

Largest intercept, *a*, is the linear dimension between its pedicel end and apex end. Largest intercept normal to (*a*); i.e., *b*, is its second dimension, which is the basis for sorting black pepper. Ten berries of black pepper were drawn at random from each of the 20 lots. The head of a paper pin was dipped in an adhesive and then attached to a point near pedicel end of the berry and allowed to dry. The point near the pedicel end of the berry was so selected that the pin attached to it did not obstruct the measurement of the three intercepts, which were perpendicular to each other. Using a micro-dial gauge (least count: 0.01 mm) the intercepts were measured.

4.3.1.4 Sphericity

Black pepper berries are globular or nearly spherical. The sphericity was determined making use of the length of the three largest intercepts measured earlier as stated in Section 4.3.1.3. The sphericity was then calculated as:

$$Sphericity = \frac{\sqrt[3]{abc}}{a} \qquad \text{...(4.3)}$$

4.3.1.5 Volume

The volume of black pepper was determined using Beckman's *Air Comparison Pycnometer, Model 930* (least count: 0.01 cm^3). Teckchandani (1988) also used the same apparatus. A sample containing 100 berries was taken at random from one of the 20 lots. It was put into the sample cup of the instrument. After operating the pistons the reading was taken from the digital counter, which provided directly the volume. The experiment was replicated five times for each of the 20 sample lots.

4.3.1.6 Specific gravity

The volume obtained in the experiment cited above was used in the determination of specific gravity. The weight of berries required in determining the specific gravity was obtained by weighing the same 100 berries used in the determination of volume. The specific gravity was calculated from these considering the density of distilled water as 0.995 g/cm^3 at 32^0 C at 1 atmospheric pressure.

4.3.1.7 1000-grain weight

From each of the 20 lots of black pepper, a sample weighing nearly 1000 g was drawn. Each lot was uniformly spread over a circular area on the floor. This was divided into five equal sectors radially. One sample containing 1000 grains was drawn randomly from each of the five sectors. These five samples provided five replications for each of the lots. These were weighed on an electronic weighing balance (least count: 1.0 mg). This experiment was repeated for all the 20 lots. From the 1000-grain weight determined for each sample, the average weight of a berry was determined by dividing 1000-grain weight by 1000.

4.3.1.8 Bulk density

OHAUS Weight per *Hectolitre Tester* (*OHAUS Bulk Density Apparatus*, Ohaus Scale Corporation, New Jersey) was used in determining bulk density. Teckchandani (1988) too used the same. From each of the 20 lots a sample weighing approximately 500 g was put in the hopper of the bulk density meter. The weighing bucket was kept below and the gate at the bottom of the hopper was opened. The bucket was filled with black pepper till it spilled. Using a strike-off stick excess material was removed. The bucket along with the black pepper was weighed on the balance. Reading gave bulk density directly in kg/hectolitre. After weighing, the material was returned to its respective original sample. After mixing thoroughly lots were again drawn and tested as described. The experiment was replicated five times for each of the 20 lots.

4.3.2 Determination of engineering properties of black pepper

The engineering properties studied were the angle of repose in piling, the coefficient of rolling friction, and the coefficient of sliding friction. The methods adopted were based on the references cited under Section 4.3.1. The report of Molenda *et al.* (2000) was specifically on the engineering property of friction of wheat on corrugated and smooth galvanized iron surfaces. The screen element, hopper, etc., used in the present study was galvanised iron.

4.3.2.1 Angle of repose in piling

A truncated cone-shaped galvanised steel hopper of 500-cm^3 capacity was mounted on a stand, with its bottom at a height of 10 cm from the floor. Its opening at the bottom was 3 cm in diameter and was provided with a gate. A square galvanised steel sheet of 1 m^2 was placed on the floor below the hopper since the angle of repose was to be found out on this material which was to be used for fabricating the trommel element, the hopper, and the chutes. A sample each was drawn from the 20 lots. Each sample was filled in the hopper and the gate was opened permitting the black pepper to pile up on the galvanised steel sheet. The maximum height and the diameter of base of the pile were recorded for determining the angle of repose. Diameter of the base was measured in four radial directions and the mean was taken. The boundary or periphery of the base was taken as the circumference encompassing the contiguous bulk of black pepper. The area, in which the black pepper remained scattered due to rolling, was not considered. The experiment was replicated five times. Angle of repose was determined as:

$$Angle\ of\ repose\ (\theta_i) = \tan^{-1}\frac{2h_i}{D_i} \qquad ...(4.4)$$

where h_i = maximum height of pile, cm; and
D_i = mean base diameter of pile, cm.

4.3.2.2 Coefficient of rolling friction

The coefficient of rolling friction too was determined on the galvanised steel surface for the same reason stated in the previous Section. A galvanised steel tilting plate was hinged to the base of a pedestal. A protractor, with a plumb bob suspended from its centre using a nylon string, was attached to the bottom of the tilting plate. A small hand-operated winch mounted on top of the pedestal operated the tilting plate through another nylon string. Depending upon the direction of rotation of the winch, the tilting plate moved upward or downward in the vertical plane. Two hundred berries, randomly selected from the whole lot, were divided into 40 groups of five berries each. The tilting plate was initially adjusted to the horizontal position. The plumb bob and the protractor indicated horizontality. A sample of five berries was placed on the galvanised tilting plate. The winch was rotated by hand and the tilting plate got tilted upwards about its hinge axis. As the inclination of the plate reached the angle of rolling friction, the berries started rolling downwards. The number of berries, which started rolling at each angle, and the corresponding angles were noted. The experiment was repeated for all the 40 groups of samples. The coefficient of rolling friction is calculated as:

$$Coefficient\ of\ rolling\ friction\ (\mu_r) = \tan\theta_r \qquad ...(4.5)$$

where θ_r = angle of rolling friction, ^{0}.

4.3.2.3 Coefficient of sliding friction

The coefficient of sliding friction too was determined on the galvanised steel surface. The same tilting plate mechanism as used in determining the coefficient of rolling friction was used in this study. Six hundred berries were randomly drawn from the whole lot. Using an epoxy adhesive three berries were pasted together on their sides forming a triangle. Care was taken to see that the adhesive did not smear the bottom surface of the grains. If smeared, the samples were rejected. The black pepper was prevented from rolling by preparing the sample in this manner. From 600 berries, 200 sample stocks were prepared. One sample was placed on the tilting plate after adjusting it to the horizontal position. Upon changing the angle of tilting plate as stated in the preceding Section, the sample became unstable at some angle and started sliding down. The angle that initiated the motion was noted. The experiment was repeated for the remaining samples. The coefficient of sliding friction is given as:

$$\textit{Coefficient of sliding friction } (\mu_s) = \tan \theta_s \qquad ...(4.6)$$

where θ_s = angle of sliding friction, ^{0}.

4.3.3 Experiments on manually-operated flat tray sieve

The feedstock used for the experiments was the three lots of black pepper available on the farm. Its moisture content was determined first. Content of fines in the feedstock was determined next before starting the experiment by using a test sieve. Then, black pepper weighing 2 kg, taken directly from a lot, was placed on the experimental sieve. Two experienced persons held it from opposite ends. It was shaken as usual. Weight of feedstock was selected based on the approximate quantity usually sieved by them. It was standardised as 2 kg. The sieving was stopped intermittently for subjecting the tailings to analysis for the amount of undersize berries in it, *i.e.*, screening inaccuracy. It was determined using Eqn (3.8). This material was, then, returned to the sieve and the shaking continued. The process of alternate shaking and analysis continued for one sample till the screening inaccuracy was reduced to finally less than five per cent. The time taken to reduce the screening inaccuracy to 20, 15, 10, and 5 per cent, with a unilateral tolerance of –2 per cent, was recorded during the course of the experiment. This experiment was conducted for 3 samples of each lot.

4.3.4 Experiments on oscillating flat screen

The feedstock was from one lot of black pepper available with the trader. Moisture content was determined by the method cited in Section 4.3.1.2. The undersize-berry content in the feedstock was also initially determined by test sieving. The levels of feed rate selected were 150, 250, and 350 kg/h, which were the mean feed rates corresponding to three existing settings of the screen. Cone pulleys on the machine were suitable for giving oscillating frequencies of 6, 8, and 12 Hz. Frequency of oscillation was first adjusted to 6 Hz. Screen was operated after filling the hopper with the sample of one feed composition. Hopper gate setting was adjusted to the lowest level of feed rate. The feed arrangement was capable of attaining steady state condition within 45 s. This had been ascertained at the beginning itself in a preliminary study by successively collecting the tailings and the fines, and weighing. However, in the experiments, measurements started only from the 60^{th} second. A stopwatch was used for measuring time. Samples were instantly collected from the tailing outlet at the 60^{th}, 80^{th}, 100^{th}, and 120^{th} second of starting the machine, weighed, and analysed for the weight of fines in tailings. Screening process was never interrupted in between during the period of an experiment. The experiment was conducted for all the feed-rate levels at each of the three frequencies and for the two feed compositions. Three replications were made for each treatment.

Experiments on clogging were carried out separately since the machine had to be stopped at certain time intervals. After starting the experiments, as stated above, the feed to the machine was cut-off at the 60^{th} second from the start. But, screen oscillation was allowed to continue till the discharge of loose material from the screen ceased. Thereupon, the material trapped in the holes were collected and weighed. This experiment was conducted for all the treatment combinations involving three frequencies, three feed rates, and two feed compositions for the four screen durations of 60, 80, 100 and 120 s. For each screen duration, a separate experiment was conducted. Each treatment was replicated thrice.

4.3.5 Testing of the drive system of trommel for input-output characteristics

Firstly, the 0.5-hp electric motor, together with the belt drive and the speed reduction gearbox, was tested using the prony brake dynamometer to find out the input-output power characteristics of the drive system. After applying the brake loads ranging from 0.5-5.0 kg in steps of 0.5 kg, the input power to the motor was adjusted, using its controller, to regulate the shaft speed to 10, 15, 20, and 25 r/min for each of the load. Simultaneously, the input power to the system for each combination of brake load and shaft speed was measured with a wattmeter and recorded. Power output was calculated using Eqn (3.7) given in Section 3.2.1 and substituting in it the brake-arm length of 0.25 m, and the brake loads and speeds cited above. Calibration curves were then plotted between input power and output power. Second part of this experiment involved the measurement of power input to the trommel at no-load and loads. This is described in the Section that follows.

4.3.6 Experiments on trommel performance

The feedstock to be used for the experiments employing the hexagonal flighted-trommel was specially prepared. The ungarbled black pepper available in the market had different proportions of oversize material. To standardize the feedstock for experiment purpose, the black pepper samples were first classified by sifting manually on test sieves having the aperture diameters of 4.00, 4.25, and 4.75 mm. The various fractions were then mixed in appropriate proportions to obtain the four levels of feed compositions. The proportions of different sizes of black pepper in the feedstock used for each of the sieves were as given in Table 4.9.

To study the effect of various parameters on trommel performance the trommel inclination was adjusted to 4°. This was made constant for all the studies. This inclination corresponds to that indicated by Bosoi *et al.* (1990). Preliminary trials too showed that this inclination produced better results. Feedstock weighing 5 kg was prepared in the desired proportion, as mentioned above, and put into the hopper after stirring properly. After switching on the motor, the speed of trommel was regulated to the chosen level. Input power to the whole drive system was recorded from the wattmeter readings. This became the power input at no-load. The regulator gate of feed hopper was, then, opened and the speed readjusted to the initial level. A cloth covering all the discharge points collected the initial discharge from the trommel during initial stabilization period. The material collected for a period of 30 s was weighed quickly to determine the feed rate. The gate was then readjusted, if necessary, and the procedure was repeated till the predetermined level of feed rate was obtained. The feed material taken out was returned to the hopper after stirring. On stabilization of feed rate, the cloth was removed and the set of trays was instantaneously placed below the trommel. To facilitate this, the trays were placed in another big tray so that all the trays could be moved together. A stopwatch was started simultaneously. The screening was effected for such a period that nearly 2 kg of feedstock was screened. On termination of the screening duration, the trays were instantaneously withdrawn. The material in each of the trays was weighed separately and recorded.

Table 4.9 Proportion of different sizes of black pepper in the feedstock for the four levels of feed composition

Feed Composition	Weight of Black Pepper Fraction, kg V[1]	L[2]	M[3]	S[4]	Total kg
For trommel of aperture diameter = 4.75 mm					
0.150	0.750	1.000	1.500	1.750	5.0
0.325	1.625	1.000	1.000	1.375	5.0
0.500	2.500	1.000	1.000	0.500	5.0
0.675	3.375	1.000	0.500	0.125	5.0
For trommel of aperture diameter = 4.25 mm					
0.150	0.250	0.500	2.000	2.250	5.0
0.325	0.125	1.500	2.000	1.375	5.0
0.500	0.250	2.250	1.250	1.250	5.0
0.675	0.375	3.000	1.500	0.125	5.0
For trommel of aperture diameter = 4.00 mm					
0.150	0.250	0.250	0.250	4.250	5.0
0.325	0.100	0.150	1.375	3.375	5.0
0.500	0.200	0.300	2.000	2.500	5.0
0.675	0.175	0.200	3.000	1.625	5.0

[1] V : black pepper retained on sieve of aperture diameter, 4.75 mm
[2] L : -do-, 4.25 mm
[3] M : -do-, 4.00 mm
[4] S : black pepper screened through aperture diameter, 4.00 mm

The wattmeter reading during the screening operation, *i.e.*, the power input at load and no-load, was noted along with the time. It was, however, done for only the 16 treatments involving four levels each of feed rate and trommel speed but related to only one feed composition, which was 0.675. Others were not taken because the feed composition was not considered to exert appreciable influence on power requirement compared to the feed rate and the trommel speed. The black pepper, clogging the apertures, were tapped out, collected, and weighed. Each treatment was replicated six times. The experiments were further continued separately for generating the observed values of screening inaccuracy required for determining the deviation of the values of screening inaccuracy observed and those predicted using the semi-empirical and empirical models developed in this study.

4.3.7 Experiments for determining the correction factor, C_o

For measuring the actual hold-up by weight of oversize material in the trommel, which was required for the determination of the values of C_o, the hopper was filled with only the oversize material. After adjusting the feed rate and the trommel speed to the desired levels, the feedstock was fed to the trommel until the system achieved steady state. After this, the feed from the hopper was abruptly stopped and simultaneously a fresh tray was placed at the discharge end of trommel to receive the material being discharged from it after the feed had been cut-off. The trommel was stopped only after its entire content was discharged. This material, together with that clogging the apertures, was weighed. This formed the actual oversize-material hold-up. The experiments were continued as per the research plan given in Section 4.1.6. Also, the experiments were repeated separately for generating the observed values of C_0 required for determining the deviation of the values of C_0 observed and those predicted using the empirical models developed in this study.

4.3.8 Experiments for determining the correction factor, C_u

To determine the values of C_u, the actual hold-up of oversize-undersize mixture was measured in the same manner as used for the determination of C_o. But, the feedstock consisted of a mixture of both oversize and undersize black pepper in the desired proportion. A large funnel-shaped chute covering the entire length and width of the trommel element, and another chute covering the discharge outlet guided the fines and tailings into the same tray. This facilitated the checking of steady state. After attaining steady state, the feed was abruptly stopped as before and the fines and tailings occurring thereafter were collected in fresh trays. But two trays were used; one for collecting the fines and the other for collecting the tailings separately. The trommel was stopped after its entire content was discharged. The particles clogging the apertures were collected in the tray for the tailings. Combined weight of tailings and fines gave the actual mixture hold-up. The experiments were continued as per the research plan outlined in Section 4.1.6. Also, the experiments were continued separately for generating the observed values of C_u required for determining the deviation of the values of C_u observed and those predicted using the semi-empirical and empirical models developed in this study.

4.3.9 Evaluation of manually-operated flat tray sieve

The readings obtained in the experiments cited in Section 4.3.3 were used in the evaluation. From the time taken to reduce the content of undersize berries in the tailings to 20, 15, 10, and 5 per cent, with a unilateral tolerance of –2 per cent, and the weight of sample sieved, the output per man-h was determined. The unit cost of sieving was also determined from this for the existing wage rate of Rs 25/man-h.

4.3.10 Evaluation of oscillating flat screen

From the weights of the tailings and the undersize berries in tailings, which were obtained in the experiments mentioned in Section 4.3.4, the screening inaccuracy was determined using Eqn (3.8). Similarly, from the total weight of berries trapped in the apertures, and the weight of one berry, the number of apertures clogged was determined. The clogging index was calculated from this using Eqn (3.10).

4.3.11 Evaluation of the performance of hexagonal flighted-trommel

The readings obtained in the experiments cited in Section 4.3.6 were used in the evaluation. Screening inaccuracy was determined after separating the fines from the tailings by sieving in a hand-shaken test sieve. The sieving continued till only one to three berries fell in five cycles of shaking. The weight of tailings and the weight of fines separated from it were recorded. The weight of berries clogging the apertures was added to the weight of tailings to make the total weight of tailings. Weight of fines in tailings was then expressed as a percentage of the total weight of tailings as given by Eqn (3.8).

Similarly, from the weight of fines collected from the respective trays covering each 15-cm zone of the trommel, the weight of fines passed through the apertures of each zone was expressed as a percentage of the weight of undersize material, which entered that zone during the entire duration of that experiment. The weight of undersize material, which entered a zone, is the difference in weight between the total weight of undersize material that entered the trommel, and the total weight of fines that passed through the apertures in all the preceding zones during the entire duration of experiment. It was estimated using Eqn (3.9).

Clogging was assessed on the basis of clogging index. The total weight of berries clogging the apertures at the end of each experiment was collected and weighed. From the 1000-grain weight, the number of berries constituting this bulk was determined. By comparing this with the total number of holes on the trommel surface the clogging index was determined as in Eqn (3.10).

4.3.12 Evaluation of the power requirement of hexagonal flighted-trommel

Using the calibration curves, cited in Section 4.3.5, for the input-output power characteristics of the system, the power requirement of hexagonal flighted-trommel was determined from the actual power input to the system during trommel operation.

4.3.13 Determination of correction factors, C_o and C_u

Values of C_o were determined by substituting the values of trommel parameters and weight of actual oversize-material hold-up in Eqn (3.18). Similarly, by substituting in Eqn (3.20) the values of trommel parameters, values of C_o, and actual oversize-undersize mixture hold-up, the values of C_u were determined. The input values were obtained from their respective experiments described in Sections 4.3.7 and 4.3.8.

4.3.14 Determination of screening inaccuracy from C_o and C_u and its comparison with experimental results

From a measurement of the feed composition of feedstock and the total feed rate, the feed rate of undersize black pepper was determined. By substituting in Eqn (3.22) the values of total feed rate, feed rate of undersize material, and those of the correction factors, C_o and C_u, the values of screening inaccuracy were predicted. These were then compared with the results obtained in the experiments described in Section 4.3.6.

The experiments conducted using the materials and methods described in this Chapter have led to satisfactory results, many of which can find application in the field. These results are presented and discussed in the Chapter that follows.

Chapter 4

RESULTS AND DISCUSSION

Results based on analyses of the data collected are discussed and presented in this chapter. These are organised mainly under the following heads.

5.1 Physical Properties of Black Pepper

5.2 Engineering Properties of Black Pepper

5.3 Performance of a Manually Operated Flat Tray Sieve

5.4 Performance of an Oscillating Flat Screen

5.5 Prediction of Screening Inaccuracy of a Hexagonal Flighted-Trommel using a Semi-Empirical Model

5.6 Performance of a Hexagonal Flighted-Trommel

5.7 Prediction of Screening Inaccuracy of a Hexagonal Flighted-Trommel using Empirical Models

5.8 Comparison of the Models Used for Predicting Screening Inaccuracy of a Hexagonal Flighted-Trommel

5.1 Physical Properties of Black Pepper

Results of the experiments on physical properties are presented in Appendix-B (Tables B-1 through B-6), and their mean values along with standard deviations are given in Table 5.1. Values obtained by Teckchandani (1988) for pigeon pea, which has some similarities in size and shape to that of black pepper, are also furnished in Table 5.1 for a comparison.

5.1.1 General appearance

The black pepper collected from the markets was dark brown to pitch black in colour. From a visual observation, the bold and as well the light berries appeared to be globular or nearly globular. The berries generally possessed a wrinkled surface. Some had even a plain surface. The bulk of black pepper had all its natural fractions like the bold pepper, light pepper, and pinheads. The produce was nearly one month old after the harvest.

5.1.2 Moisture content

Moisture content of the samples used in the measurement of properties and in the other experiments was determined on the basis of its dry weight and wet weight (Table B-1).

The data indicate that the moisture content was below the upper limit of 11.5 per cent prescribed by the Agmark Grade Specifications given in Table 1.3. Therefore, the sample suited well as a feedstock for the experiments.

Table 5.1 Properties of black pepper (*In comparison with that of pigeon pea)**

Sl. No.	Property	Black Pepper		Pigeon Pea*
		Value	Standard Deviation	Value
1	Moisture Content, %			
	Wet basis	9.1	0.47	8.0
	Dry basis	10.1	0.58	---
2	Size, mm			
	Largest intercept, a	4.54	0.4	4.07
	Largest intercept normal to (a), b	4.28	0.41	4.69
	Largest intercept normal to (a) & (b), c	4.27	0.41	5.61
3	Sphericity, (-)	0.96	0.02	0.848
4	Volume, mm^3	47.0	7.0	56.02
5	Specific gravity, (-)	1.1	0.05	---
6	Bulk density, kg/m^3	554.6	43.4	784.0
7	1000-grain weight, g	50.291	8.02	72.4
8	Single-grain weight, g	0.05	0.008	---
9	Angle of repose, °	37.7	1.32	28.9
10	Coefficient of rolling friction, (-)	0.29	6.8	0.36
11	Coefficient of sliding friction, (-)	0.50	7.1	---

* As determined by Teckchandani (1988)

5.1.3 Physical dimensions

Screening through circular apertures is brought about on the basis of second dimension of the material. Results of measurement of the three intercepts normal to each other are presented in Table B-2. Grand means of the three intercepts are given in Table 5.1. It is evident from the data corresponding to the second dimension of berries that some berries would get retained on a screen of aperture diameter 4.75 mm whereas some would pass through an aperture 4.00 mm in diameter. Therefore, the feedstock adequately covered the range of size required for the experiments. The different feed compositions required in the experiments were prepared from this by fractionating it into different size grades.

5.1.4 Sphericity

The orientation of a pepper berry during its cascading in a trommel is partly controlled by its sphericity, which also decides the axis about which it rolls. The sphericity was determined based on its physical dimensions given in Table B-2. The values of sphericity are also presented in the same table. In general, the black pepper was globular or nearly globular. The bold and light berries, when put into motion, moved more by rolling than sliding. The grand mean value of 0.93 in Table 5.1 confirmed that the bold and light black pepper berries used in the experiments were almost spherical. A comparison with the sphericity of 0.848 of pigeon pea, as determined by Teckchandani (1988), indicates that the black pepper is more spherical.

5.1.5 Volume

The values of volume, determined in the experiments, are presented in Table B-3. Percolation of a particle, from an upper layer to a lower layer, through a bed of granular materials is known as *trickle stratification*. It takes place on a vibrating screen during the screening. It is partly controlled by the volume of particles. Smaller particles percolate faster (Moysey *et al.*, 2004). As the pinheads were much smaller in size than the grand mean volume of 47 mm^3 of the bold berries, they percolated faster and made their exit through the apertures. Pinheads were not at all detected in the tailings collected during the experiments. It was, further, observed that the separation of pinheads was completed in the first half itself of the screen.

5.1.6 Specific gravity

Specific gravity plays an important role in effecting the trickle stratification in the presence of vibrations. The values of specific gravity of the samples tested are presented in Table B-3. Though there were some light berries having specific gravity less than 1.0 the higher specific gravity of bold pepper caused the means of samples to be above 1.0. Light berries normally float in water. In the standard tests, a berry is designated a *light berry* if it floats when stirred in alcohol or methylated spirit of 0.80 to 0.82 specific gravity at a room temperature around 25° C (Anon., 1995).

5.1.7 1000-grain weight

Tables 5.1 and B-4 show that grand mean of 1000-grain weights was 50.291 g. So, the mean weight of a berry was about 0.05 g. At this rate, the average number of berries in a kilogram of black pepper was about 20000. The number of apertures clogged on a screen was calculated based on the single-grain weight and the total weight of trapped berries taken out from the apertures at one instant.

5.1.8 Bulk density

In deciding the capacity of storage structures, information on bulk density of the material is essential. The grand mean bulk density obtained for the black pepper was 554.6 kg/m^3 (Table B-4). This was used mainly in designing the hopper and the chutes. It is seen, further that the bulk density of black pepper was smaller than that of the pigeon pea.

5.2 Engineering Properties of Black Pepper

To some extent, properties like angle of repose, coefficient of rolling friction, and coefficient of sliding friction control the movement of particles in a screening equipment. Results of the studies on these are presented and discussed below.

5.2.1 Angle of repose in piling

Values of the angle of repose in piling of black pepper varied from 35.2°-39.6° with its mean at 37.7° (Table B-5). Though the berries were globular or nearly globular, the higher values were due to their surface roughness caused by the wrinkles. In comparison, pigeon pea had a lower value; might be because of its smoother surface. The hopper bottom and the guide chutes were accordingly provided an angle greater than this. It helped in the complete emptying of the hopper and the chutes.

5.2.2 Coefficient of rolling friction

The values of coefficient of rolling friction, determined on an inclined galvanised steel surface, are presented in Tables 5.1 and B-6. Rolling took place at angles in the range 5°-27°. For a mean angle of 16°, the coefficient of rolling friction was 0.29. Higher values of rolling friction, wherever they occurred, appeared to be because of the berry's wrinkled surface. In its natural position, the berry rests on the edges of, may be, a crater or more. Therefore, it requires a higher angle to become unstable. Smaller angles observed were of the berries, which had smaller and shallow craters, or a plain surface. The, pigeon pea recorded a higher mean coefficient of rolling friction. Reason for the same has not been recorded by the investigator. Higher value might be because of its lower sphericity.

5.2.3 Coefficient of sliding friction

The values of coefficient of sliding friction of black pepper on a galvanised iron surface show that the mean is 0.48 corresponding to an angle, 25.8° (Table B-6). Sliding occurred in the range 15°-38°. In the experiment on rolling friction, it was noticed that individually the berries tended to first roll than slide even with its wrinkled surface. This indicated that the overall shape was more favourable for rolling than sliding. But in bulk, the grains generally moved by sliding; might be due to interlocking of the surfaces of adjacent berries at the wrinkles.

The data, as reported above, provided useful information on the black pepper, which was used as the feedstock. It could also be used in the design of the experimental set-up and the analyses of data.

5.3 Performance of a Manually-Operated Flat Tray Sieve

Results of testing and evaluation of the manually operated flat tray sieve are presented and discussed below. Initial quantities of the undersize berries in the three lots of feedstock used in the experiments were as in Table 5.2 below.

Table 5.2 Undersize-berry content in the feedstock used in manual sieving

	Undersize-berry Content in Feedstock, %		
	Lot No. : 1	Lot No. : 2	Lot No. : 3
Range of values (*Replications: 6*)	67.4 – 76.2	70.3 – 79.6	65.3 – 71.7
Mean	**71.4**	**76.2**	**68.2**
Standard deviation	*3.0*	*3.2*	*2.4*

Though it appears that the feedstock had a high percentage of undersize berries, its content was, according to the trader, only as usual. The means of moisture content, on dry weight basis, of the three lots were 9.6, 10.1, and 9.9 per cent respectively. The moisture content was well below the upper limit of 11.5 per cent prescribed by the Agmark Grade Specifications given in Table 1.3. The output and the unit cost of operation were worked out on the basis of the quantity screened, the mean time taken to reduce the screening inaccuracy to the predetermined levels, and the labour wages in Kochi on January 15, 2008. These are given in Appendix-C (Table C-1) and illustrated in Fig. 5.1.

5.3.1 Output

As expected, the general trend was for the output to decrease with the lowering of screening inaccuracy. This trend is well in agreement with the observations of Turnquist and Porterfield (1967) that optimum capacity and optimum size differentiation cannot be obtained simultaneously. At the lowest level chosen for the screening inaccuracy, the output matched with the traders' thumb-rule, which stood at 15-20 kg/man-h. The relationship between the output and the screening inaccuracy was established through regression analysis. The second-degree polynomial equation, which best represented the relationship is shown in Fig. 5.1. The rate at which the output decreased is also discernible from the same figure. Curve is the steepest between the screening inaccuracies of 20 and 15 per cent. This is because of the quicker sifting of berries, which were smaller than even the near-mesh size, in large quantities. As sifting continued, their quantity became less and less. At the same time, more number of berries having near-mesh size remained on the screen surface waiting for their turn to pass through the aperture. But, their passage did not become easy and smooth because of the very narrow clearance between their size and that of the aperture. This led to an overall delay in the process. This could be the reason for lower outputs at lower screening inaccuracies.

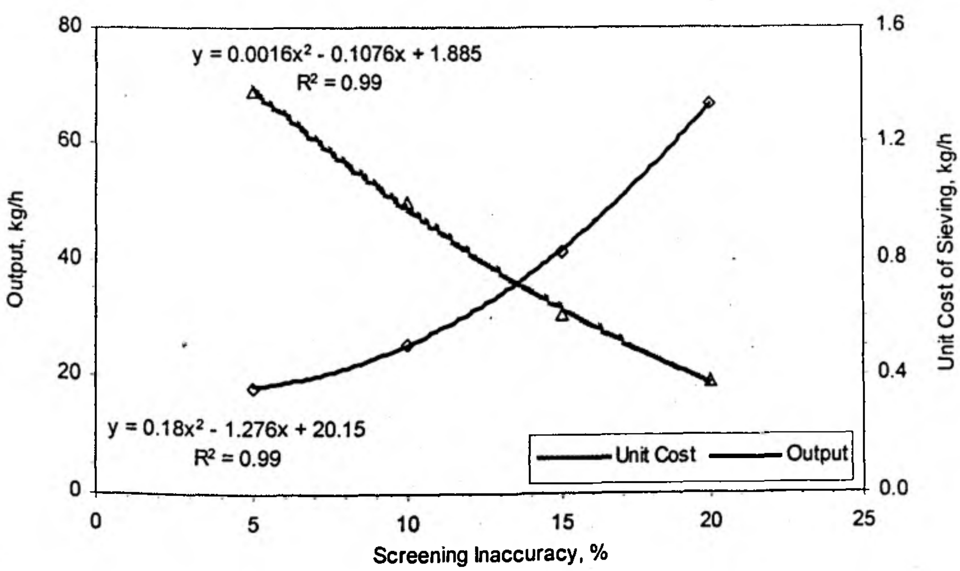


Fig. 5.1 Plot of output and unit cost of sieving against screening inaccuracy

5.3.2 Unit cost of sieving

It is evident from Appendix-C (Table C-1) and Fig. 5.1 that the unit cost of operation was higher for lower screening inaccuracies. It was because of the reduction in output. This is quite natural too. Therefore, when lower screening inaccuracy is strictly specified for the black pepper, one should be ready to accept the corresponding reduction in output and the increase in unit cost of sieving. In spite of these disadvantages, manually operated sieves shall continue to be in use, especially where the labour is in surplus and the quantity to be sieved is not large.

Based on the above, it is concluded that, in using a manually operated flat tray sieve for size classifying black pepper: (1) optimum output and optimum size differentiation cannot be achieved simultaneously, (2) output decreased with the decrease in screening inaccuracy, (3) outputs at the screening inaccuracies of 20, 15, 10, and 5 % (with a unilateral tolerance of –2%) were respectively 66.7, 41.3, 25.6, and 18.2 kg/man-h, (4) unit cost of sieving increased with the lowering of screening inaccuracy, and (5) unit cost of sieving at the screening inaccuracies of 20, 15, 10, and 5 % (unilateral tolerance, –2%) were respectively Rs 0.38, 0.61, 0.99, and 1.38 per kilogram.

5.4 Performance of an Oscillating Flat Screen

Results of testing and evaluation of a single-deck oscillating flat screen are dealt below. Initial quantity of fines in the feedstock, supplied by the trader, was as given in Table 5.3. A part of it was used for providing the first sample lot having a feed composition of 0.330. The other sample lot prepared from the rest of this feedstock, by manipulating the oversize-berry content to 67.5 per cent, provided the other feed composition of 0.675, which matched with the highest level chosen for the experiments with trommels.

Table 5.3 Undersize-berry content in the feedstock used in oscillating flat screen

	Undersize-berry Content in Feedstock, %
Range of values (*Replications: 6*)	65.8 – 68.9
Mean	**67.1**
Standard deviation	*1.1*

It can be seen from Table 5.3 that the undersize-berry content was only in the normal range. The moisture content too was well within the maximum limit of 11.5 per cent prescribed by the Agmark Grade Specifications given in Table 1.3. The three parameters studied included the screening inaccuracy, clogging index, and the output.

5.4.1 Screening inaccuracy

The screening inaccuracies determined are presented in Appendix-C (Table C-2). The parameters and their levels selected were; (i) feed composition (0.330 and 0.675), (ii) feed rate (150, 250, and 350 kg/h), (iii) oscillation frequency (6, 8, and 12 Hz), and (iv) screening duration (60, 80, 100, and 120 s). Result of the analysis of variance (ANOVA) using the data in Table C-2 is given in Table 5.4.

Table 5.4 ANOVA for the effect of feed composition, feed rate, oscillation frequency, and screening duration, on screening inaccuracy of oscillating flat screen

Source of Variation	df	SS	MSS	Computed F
Feed Composition (F_C)	1	19083.88	19083.88	5590.45**
Feed Rate (F_T)	2	3567.23	1783.61	522.49**
Oscillation Frequency (O_{fr})	2	3282.02	1641.01	480.72**
Screening Duration (T_s)	3	463.48	154.49	45.26**
F_C x F_T	2	273.84	136.92	40.11**
F_C x O_{fr}	2	118.98	59.49	17.43**
F_C x T_s	3	9.95	3.32	0.97NS
F_T x O_{fr}	4	80.88	20.22	5.92**
F_T x T_s	6	46.41	7.74	2.27*
O_{fr} x T_s	6	5.97	1.00	0.29NS
F_C x F_T x O_{fr}	4	208.24	52.06	15.25**
F_C x F_T x T_s	6	21.94	3.66	1.07NS
F_C x O_{fr} x T_s	6	6.93	1.16	0.34NS
F_T x O_{fr} x T_s	12	20.76	1.73	0.51NS
F_C x F_T x O_{fr} x T_s	12	23.47	1.96	0.57NS
Error	144	491.57	3.41	
Total	215	27705.54		

* Significant at 5 per cent level ** Significant at 1 per cent level

NS Non-significant

It shows that main effects of all the four parameters were highly significant. The results and the discussion presented below show as to how they influenced screening inaccuracy.

5.4.1.1 Effect of feed composition

It is seen from Table C-2 and Figs. 5.2 through 5.4 that, with no exception, the change in feed composition from 0.330 to 0.675 decreased screening inaccuracy, at all the selected levels of feed rate, oscillation frequency, and screening duration. Black pepper being a particulate material, the feed composition decided the number of undersize berries in unit bulk. As the feed composition changed from 0.330 to 0.675, only lesser number of undersize berries appeared in the feed and thereby on the screen surface at any instant. Consequently, only fewer numbers had to compete for the available apertures on the screen element. As a result, from the undersize berries, the proportion of berries that became successful in passing through the apertures increased. This led to having lesser quantity of undersize berries in the tailings and resulted in lower screening inaccuracies. It is to take advantage of this condition that the particulate material is passed repeatedly several times through the screen in certain processing plants. In the present study, an attempt has not been made to establish through regression analysis the relationship between screening inaccuracy and feed composition, due to the fewer factor levels made available at the test site.

5.4.1.2 Effect of feed rate

The result of ANOVA presented in Table 5.4 shows that the main effect of feed rate was second only to the feed composition. Like the feed composition, a change in feed rate varied the number of undersize berries present on the screen surface at any instant. But, the number of perforations on the screen element was constant. As a result, from the undersize berries, the percentage of berries becoming unsuccessful in getting sifted varied. This changed the screening inaccuracy. It is seen from Table C-2 and Fig. 5.2 that the overall effect was to vary the screening inaccuracy directly proportional to the feed rate at the different levels of the other parameters.

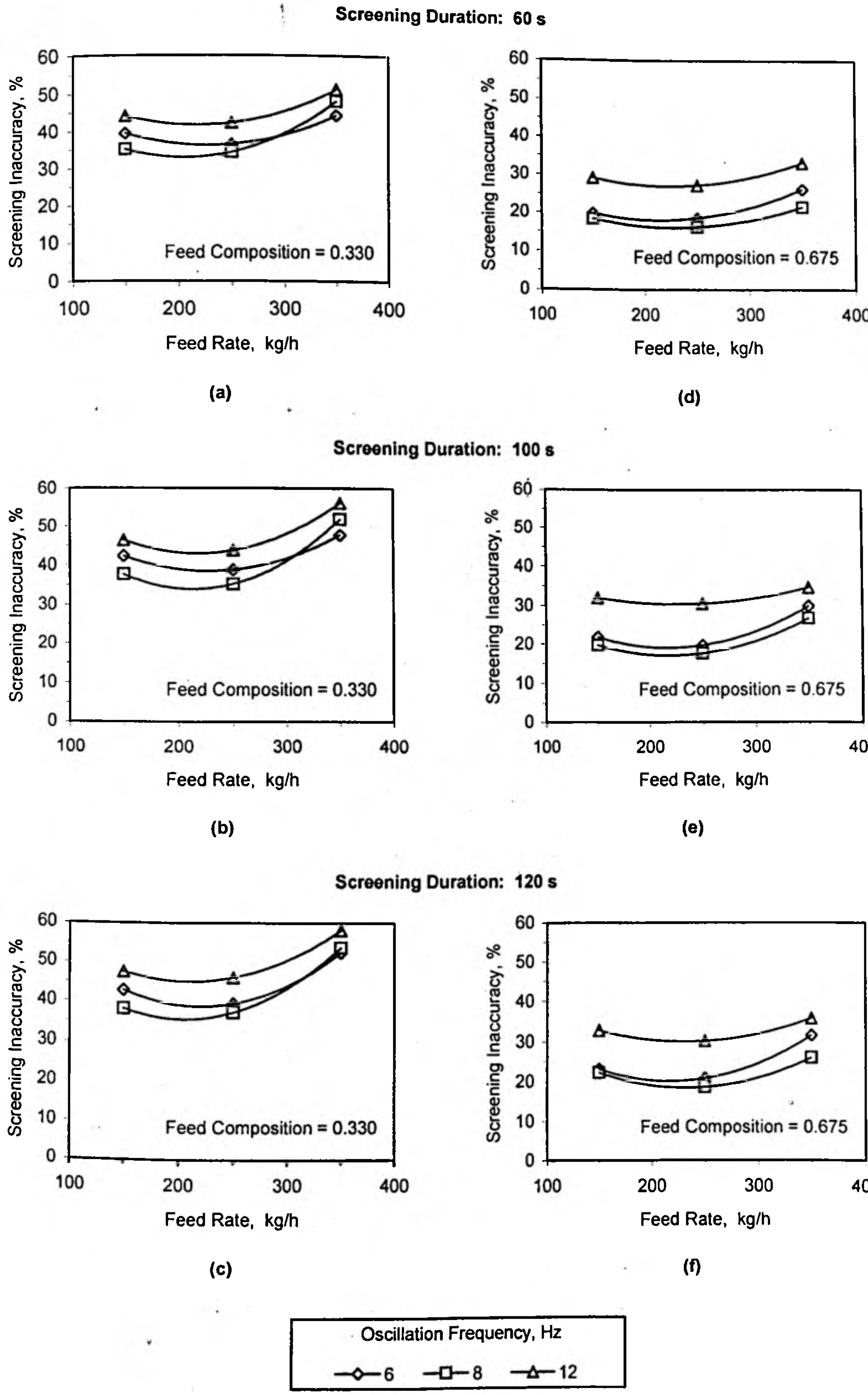


Fig. 5.2 **Effect of feed rate on screening inaccuracy of an oscillating flat screen over a range of oscillation frequencies, screening durations and feed compositions**

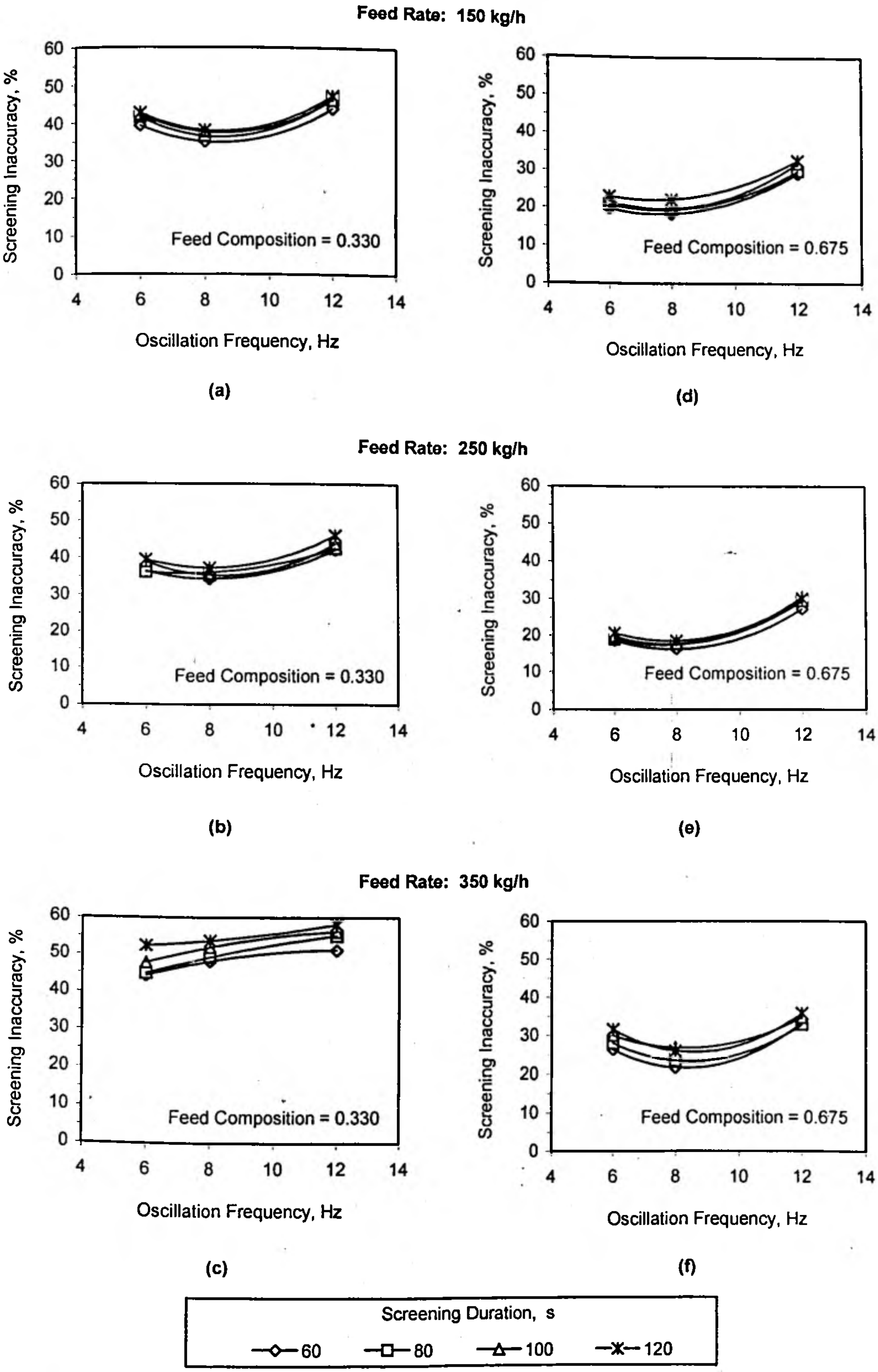


Fig. 5.3 Effect of oscillation frequency on screening inaccuracy of an oscillating flat screen over a range of screening durations, feed rates and feed compositions

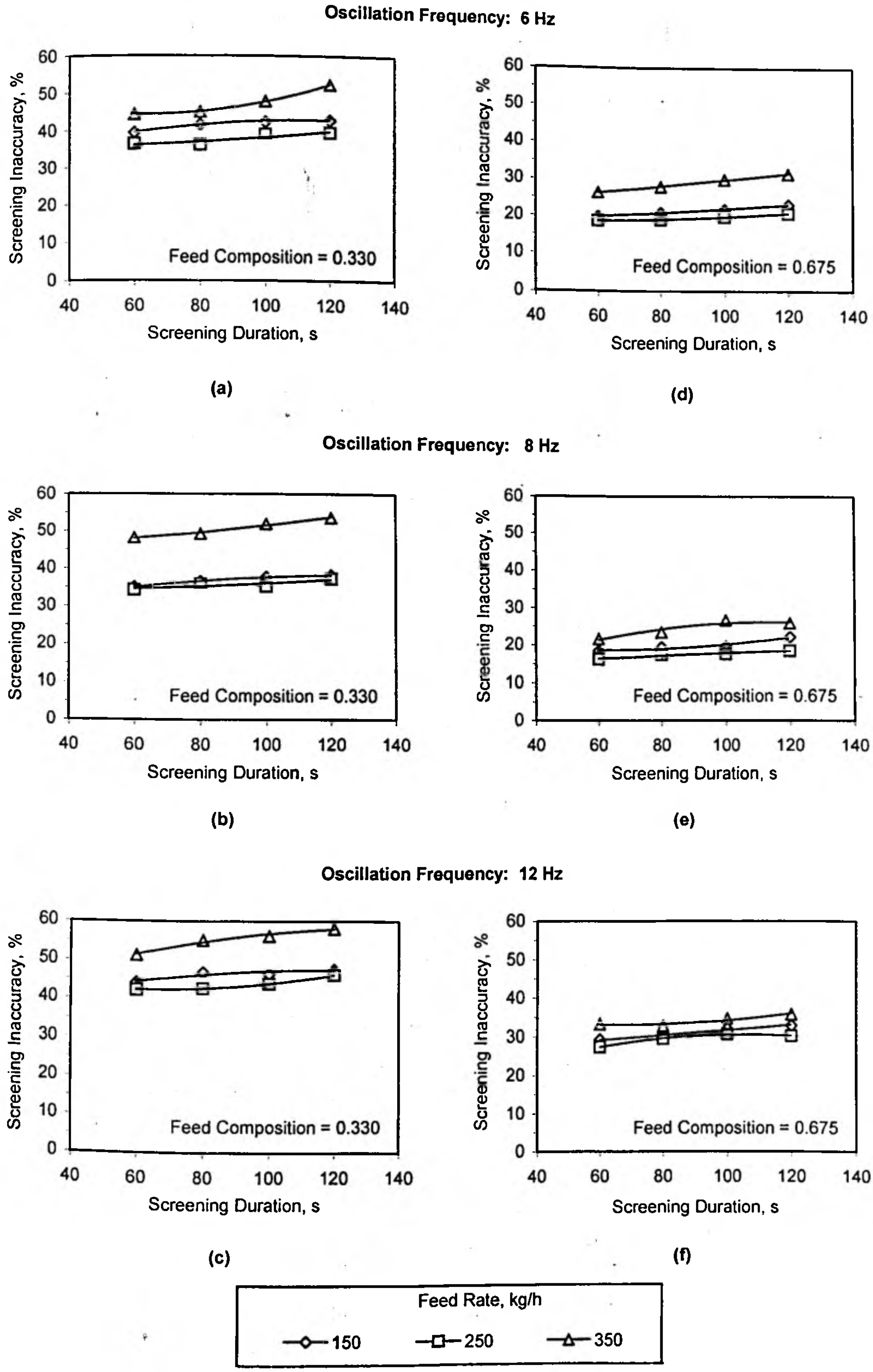


Fig. 5.4 **Effect of screening duration on screening inaccuracy of an oscillating flat screen over a range of feed rates, oscillation frequencies and feed compositions**

The relationship between the two was best represented by a second-degree polynomial equation of the following form with a high correlation coefficient.

$$S_i = a_0 + a_1 F_T + a_2 F_T^{\ 2} \qquad \ldots(5.3)$$

where S_i = screening inaccuracy, %;
F_T = feed rate, kg/h; and
a_0, a_1, and a_2 = constants.

Among the three feed rates of 150, 250, and 350 kg/h, the second produced comparatively lower screening inaccuracies. At the lowest feed rate, the population of berries on the screen was not dense and hence the particles remained widely dispersed on the screen surface. This allowed resistance-free sliding and/or rolling of the nearly spherical black pepper berries on the screen surface. This might have led to the skipping of perforations by the undersize berries. Consequently, the screening inaccuracy increased. The lowest screening inaccuracy of 15.6 per cent was at the intermediate feed rate of 250 kg/h. But, it was at the feed composition of 0.675. At the feed composition of 0.330, which corresponded to the field situation, the screening inaccuracy was 32.6-48.7 per cent at 250 kg/h. At this feed rate, the particle dispersal might be of an order conducive for particle passage. Even the motion of an adjacent particle might be aiding in the passage of a particle through the perforation. Contrary to this, the highest population density of berries occurred at the highest feed rate and it might have hindered trickle stratification of finer berries to the screen surface. This appeared to have increased screening inaccuracy. Similarly, the increased presence of oversize berries produced higher clogging indices, and thereby, higher screening inaccuracies. So, as stated earlier, there was a necessity for limiting the amount of black pepper on the screen during screening. The observations of Rose (1977) and Feller *et al.* (1986) agreed with this. In the study with peanut seeds, Feller *et al.* (1986) used a feed rate of 986 kg/h for 1m^2 of screen surface. In the present study using a screen of size, 0.9 x 0.6 m, a feed rate of even 350 kg/h, which corresponded to 648 kg/h for 1m^2 of screen surface, gave very high screening inaccuracies. This might be partly due to the wrinkled surface of black pepper and the corresponding retardation in pace while passing though the apertures. Clogging was also more because of the firm interlocking of wrinkled surface with the edge of aperture. Peanuts have relatively a smoother surface, and this aids in its quicker sliding while passing though the perforations. So, screening inaccuracy was lesser compared to black pepper. Hence, it was felt advantageous to use the present screen at the feed rate of about 250 kg/h.

5.4.1.3 Effect of oscillation frequency

The result of ANOVA shows that the main effect of oscillation frequency too was significant at 1 per cent level, though not to the extent of feed composition and feed rate (Table 5.4). The results presented in Table C-2 and Fig. 5.3 indicate that the overall effect was to increase screening inaccuracy with an increase in oscillation frequency. The relationship between the two was best expressed by a second-degree polynomial equation of the following form with a high correlation coefficient.

$$S_i = a_0 + a_1 O_{fr} + a_2 O_{fr}^2 \qquad \ldots(5.4)$$

where S_i = screening inaccuracy, %;
O_{fr} = oscillation frequency, Hz; and
a_0, a_1, and a_2 = constants.

Their relationship, however, was seen dependent on other factors too; an important one being the feed rate. For the two lower feed rates of 150 and 250 kg/h, smaller mean values of screening inaccuracy recorded were at the frequency of 8 Hz. The screening inaccuracies at the lowest and highest frequencies of 6 and 12 Hz respectively were higher than these. This showed that there was a certain frequency range somewhere between 6 and 12 Hz, which was capable of producing low values for screening inaccuracy. This confirmed also the observation of Bosoi *et al.* (1990) that certain appropriate motion was necessary to facilitate particle passage. Besides, this motion might also be helping in dislodging some of the trapped berries from the blinded apertures, thus making available more perforations for particle passage. The frequency range that was required for obtaining minimum of screening inaccuracies would be, however, different for different materials. Feller (1980) stated that the screen he tested for cottonseeds appeared to be very efficient at a frequency of 5.83 Hz, when considering particle passage alone. But, it was not so in the present study. It might be due to the detrimental effect of clogging, which was more at the frequency of even 6 Hz. At this frequency, the inertia force was not large enough to drive out most of the particles seated in the apertures. This permitted the sifting of only fewer numbers of undersize berries and caused higher screening inaccuracies.

Further, the maximum values recorded for the screening inaccuracy were at the frequency, 12 Hz. One reason for this was the increased relative velocity between the berry and the screen surface. As pointed out by Feller and Foux (1975), higher relative velocity prevented a particle from sinking deep enough into the perforation to pass through. When the particle was part of the way into the perforation, the force exerted on the particle by the perforation's edge, due to the screen's high acceleration, might drive it out of the perforation. Another reason, as given by Standish *et al.* (1986) that an increase in the frequency lengthened particle trajectory and led to lesser number of particle-contacts per unit length of the screen, also held good in the present study. Based on the above, the frequency beneficial for the screen was about 8 Hz.

5.4.1.4 Effect of screening duration

The ANOVA shows that the main effect of screening duration was the least of the four parameters (Table 5.4). One reason for this might be the short duration selected in the study. Based on the data in Table C-2, the variation of screening inaccuracy due to changes in screening duration at different levels of feed composition, feed rate, and oscillation frequency is illustrated in Fig. 5.4. A second-degree polynomial equation of the following form best represented the relationship with a high correlation coefficient.

$$S_i = a_0 + a_1 T_s + a_2 T_s^2 \qquad \text{...(5.5)}$$

where S_i = screening inaccuracy, %;
T_s = screening duration, s; and
a_0, a_1, and a_2 = constants.

The general trend was for the screening inaccuracy to increase with the prolonging of screening duration. This indicated that, for the durations chosen, the screening inaccuracy was cumulative. For a screen element, the number of perforations is fixed. Therefore, ideally, the screening inaccuracy must not change with duration under a combination of feed and operational parameters, provided all the apertures are available for particle passage at all times. But, this does not happen. The number of perforations available for particle passage goes on decreasing cumulatively with time due to clogging. This causes the screening inaccuracy to go up cumulatively. This finding is in agreement with those of the earlier researchers (English, 1974; Rose, 1977; Feller *et al.*, 1986). Since clogging cannot be totally eliminated, the only way to reduce the rate of increase of screening inaccuracy is to clear the clogged apertures by an appropriate method. The lowest screening inaccuracy observed was 15.6 per cent, which was for the duration of 60 s. This was much higher than that prescribed by the Agmark Grade Specifications given in Table 1.3. Further, it might also be not possible to reduce screening inaccuracy beyond a certain limit by shortening screening duration because every screen might have an inherent limit for screening inaccuracy.

5.4.1.5 Interaction effect

The treatment means, required for establishing the 2-variable and 3-variable interaction effects are provided in Tables 5.5 and 5.6 respectively. These are for only the four interactions found significant in the ANOVA. The means were used also for determining the level of significance pertaining to the difference between any two treatments. The values of statistical least significant difference (LSD), for the levels of significance at 1 and 5 per cent, are also furnished along with the tables. Non-significant differences were observed only in two cases.

Two-variable interaction: The interaction between feed composition and feed rate lowered the screening inaccuracy at all the levels of feed rate when the feed composition changed from the level of 0.330 to 0.675. This was due to the reduction in the number of undersize particles in the feedstock. Similarly, the change in feed rate from 150 to 250 kg/h too lowered the screening inaccuracy at both the levels of feed compositions. This was a desirable condition. But, its further increase led to considerable increase in the screening inaccuracy at both the levels of feed compositions. So, at the feed composition of 0.675 and the feed rate of 250 kg/h, the proportion of undersize and oversize particles on the screen was seen to be appropriate enough for producing lower screening inaccuracies. This indicated of the need for maintaining an appropriate feed rate for deriving lower screening inaccuracy. A pattern, same as above, existed for the interaction between feed composition and oscillation frequency. Though the lowest frequency, 6 Hz, favoured particle passage, clogging became more and this raised screening inaccuracy.

Table 5.5 **Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, oscillation frequency, and screening duration, on screening inaccuracy of oscillating flat screen**

Feed Composition (F_C) (-)	Mean Screening Inaccuracy (S_i), %										
	Feed Rate (F_T), kg/h			Oscillation Frequency (O_{fr}), Hz			Screening Duration (T_S), s				Mean
	150	250	350	6	8	12	60	80	100	120	
	%	%	%	%	%	%	%	%	%	%	%
0.330	41.53	39.05	51.07	42.21	41.11	48.34	-	-	-	-	43.88
0.675	24.09	22.07	29.10	23.24	20.58	31.44	-	-	-	-	25.09
Feed Rate (F_T), kg/h											
150	-	-	-	31.43	28.40	38.59	30.98	32.51	33.32	34.43	32.81
250	-	-	-	28.62	26.58	36.49	29.16	30.09	30.94	32.06	30.56
350	-	-	-	38.13	37.54	44.58	37.43	38.87	41.16	42.87	40.08
Mean	32.81	30.56	40.08	32.73	30.84	39.89	32.52	33.82	35.14	36.45	

LSD *for*	Significance Level 0.01	0.05
F_C	5.66	1.12
F_T	1.52	0.64
O_{fr}	1.52	0.64
T_s	1.14	0.59
$F_C \times F_T$	2.14	0.90
$F_C \times O_{fr}$	2.14	0.90
$F_T \times O_{fr}$	1.41	0.80
$F_T \times T_s$	1.37	0.85

Table 5.6 **Mean values showing 3-variable interaction effect, among feed composition, feed rate, and oscillation frequency, on screening inaccuracy of oscillating flat screen**

Feed Rate (F_T)	Mean Screening Inaccuracy (S_i), %					
	Feed Composition (F_C), (-)					
	0.330			0.675		
	Oscillation Frequency (O_{fr}), Hz			Oscillation Frequency (O_{fr}), Hz		
	6	8	12	6	8	12
kg/h	%	%	%	%	%	%
150	41.50	36.90	46.20	21.37	19.91	30.98
250	37.76	35.71	43.68	19.48	17.44	29.30
350	47.36	50.71	55.14	28.89	24.38	34.03

LSD *for*	Significance Level 0.01	0.05
$F_C \times F_T \times O_{fr}$	2.00	1.14

As it was increased to 8 Hz, clogging got reduced. Moreover, the vibrations induced in the screen element at this frequency appeared to be aiding in particle passage. But, further increase became more detrimental to the particle passage. The higher inertia forces generated by the greater screen acceleration prevented the particles from passing through the apertures. Therefore, the combination of 8 Hz and 0.330 for respectively the oscillation frequency and the feed composition was considered ideal for deriving lower screening inaccuracy.

The interaction between feed rate and oscillation frequency gave the lowest screening inaccuracies at their intermediate levels of 250 kg/h and 8 Hz. In their respective interactions with the feed compositions too, these levels presented the lowest screening inaccuracies. Therefore, the appropriateness of these levels stood further confirmed.

The interaction between feed rate and screening duration produced an ascending trend in screening inaccuracy. The main effect of screening duration was also similar. In a continuous system, new oversize particles capable of clogging the apertures flow onto the screen continuously. So, clogging becomes cumulative, and it causes the screening inaccuracy to rise. In the present study, at any screening duration, the feed rate of 250 kg/h gave the lowest screening inaccuracies. All these pointed to the need for clearing the clogged apertures at shorter intervals and maintaining 250 kg/h as the feed rate.

Three-variable interaction: An examination of the three-variable interaction among feed composition, feed rate, and oscillation frequency show that the change in level of feed composition from 0.330 to 0.675 invariably reduced screening inaccuracy for all the treatments. The intermediate feed rate, 250 kg/h, again produced lower screening inaccuracies at all the levels of feed compositions and oscillation frequencies. Situation was the same with the oscillation frequency for the feed composition, 0.675 and the three feed rates. The intermediate frequency, 8 Hz, offered lower inaccuracies. But, it was slightly different at the feed composition, 0.330, and the feed rate, 350 kg/h. The screening inaccuracy continued to increase for the change of frequency from the lowest to the highest. It was because, this combination of feed rate and feed composition brought onto the screen the maximum quantity of undersize particles. Besides, the changes in screen motion were inadequate to disperse the dense bulk of particles for effecting trickle stratification. Further, it encouraged clogging. The result was an ascending screening inaccuracy with the increase in oscillation frequency. But for this, the intermediate frequency, 8 Hz, gave lower inaccuracies at the first two levels of feed rates for the feed composition, 0.330.

Based on the details presented in this Section (Section 5.4.1), the following major conclusions were drawn on screening inaccuracy of oscillating flat screens.

1. Greater the feed composition lower was the screening inaccuracy.
2. As an overall effect, the increasing of feed rate, oscillation frequency, and screening duration was detrimental to accurate size classifying because their increase raised the screening inaccuracy.
3. The feed rate, 250 kg/h, was better than 150 and 350 kg/h for obtaining lower screening inaccuracies.
4. Even the feed rate of 250 kg/h produced screening inaccuracies as high as 32.6-48.7 per cent within 120 s from the commencement of screening, for an ungarbled feedstock collected freshly from the trader.
5. The oscillation frequency, 8 Hz, was better than 6 and 12 Hz for obtaining lower screening inaccuracies.
6. The oscillating screen studied was incapable of lowering the screening inaccuracy to the level of even 10 per cent in size classifying black pepper.

5.4.2 Clogging index

As indicated earlier, one of the factors responsible for higher screening inaccuracy of an oscillating flat screen is the clogging. The clogging indices determined are presented in Appendix-C (Table C-3). The parameters and their levels selected were the same as those used in determining the screening inaccuracy and given in Section 5.4.1. Result of the ANOVA using the data in Table C-3 is presented in Table 5.7. It shows that main effects of all four parameters were highly significant. The results and the discussion presented below show as to how they influence clogging.

5.4.2.1 Effect of feed composition

It is seen from Table C-3 and Figs. 5.5 through 5.7 that, in all cases, the change in feed composition from 0.330 to 0.675 increased clogging index. This appeared to be due to enhancement in the number of oversize berries coming onto the screen surface along with the feed. As the feed composition of black pepper changed from 0.330 to 0.675, more number of oversize berries, capable of clogging the apertures, appeared in the feed. Supply of such a feed to the screen resulted in the clogging of apertures in larger numbers leading to higher clogging indices. Therefore, oscillating flat screens would require clearing of the apertures at much shorter intervals when being used for higher feed compositions. In the present case, the variation in clogging index was seen to be more pronounced, presumably, because of the larger difference in the proportions of oversize material present in the two feed compositions. Further, due to the existence of only two levels for the feed composition, the relationship between clogging index and feed composition was not established through regression technique.

Table 5.7 ANOVA for the effect of feed composition, feed rate, oscillation frequency, and screening duration, on clogging index of oscillating flat screen

Source of Variation	df	SS	MSS	Computed F
Feed Composition (F_C)	1	4186.16	4186.16	3747.25**
Feed Rate (F_T)	2	5859.77	2929.88	2622.69**
Oscillation Frequency	2	2744.64	1372.32	1228.43**
Screening Duration (T_s)	3	1213.08	404.36	361.96**
$F_C \times F_T$	2	326.00	163.00	145.91**
$F_C \times O_{fr}$	2	147.90	73.95	66.20**
$F_C \times T_s$	3	142.26	47.42	42.45**
$F_T \times O_{fr}$	4	248.22	62.05	55.55**
$F_T \times T_s$	6	321.19	53.53	47.92**
$O_{fr} \times T_s$	6	134.13	22.36	20.01**
$F_C \times F_T \times O_{fr}$	4	3.70	0.93	0.83NS
$F_C \times F_T \times T_s$	6	7.27	1.21	1.08NS
$F_C \times O_{fr} \times T_s$	6	1.84	0.31	0.27NS
$F_T \times O_{fr} \times T_s$	12	23.87	1.99	1.78*
$F_C \times F_T \times O_{fr} \times T_s$	12	9.49	0.79	0.71NS
Error	144	160.87	1.12	
Total	215	15530.38		

* Significant at 5 per cent level ** Significant at 1 per cent level

NS Non-significant

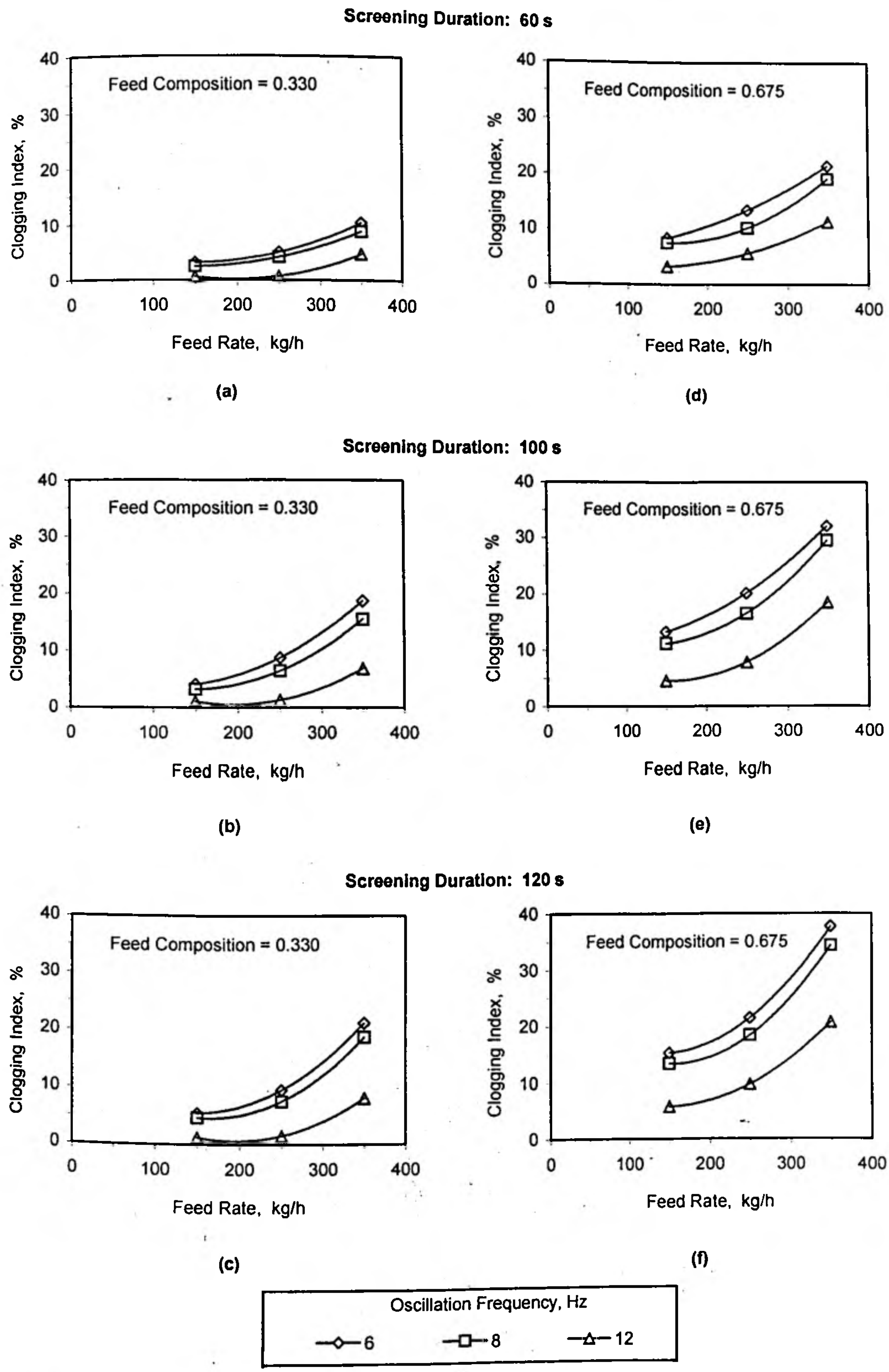


Fig. 5.5 **Effect of feed rate on clogging index of an oscillating flat screen over a range of oscillation frequencies, screening durations and feed compositions**

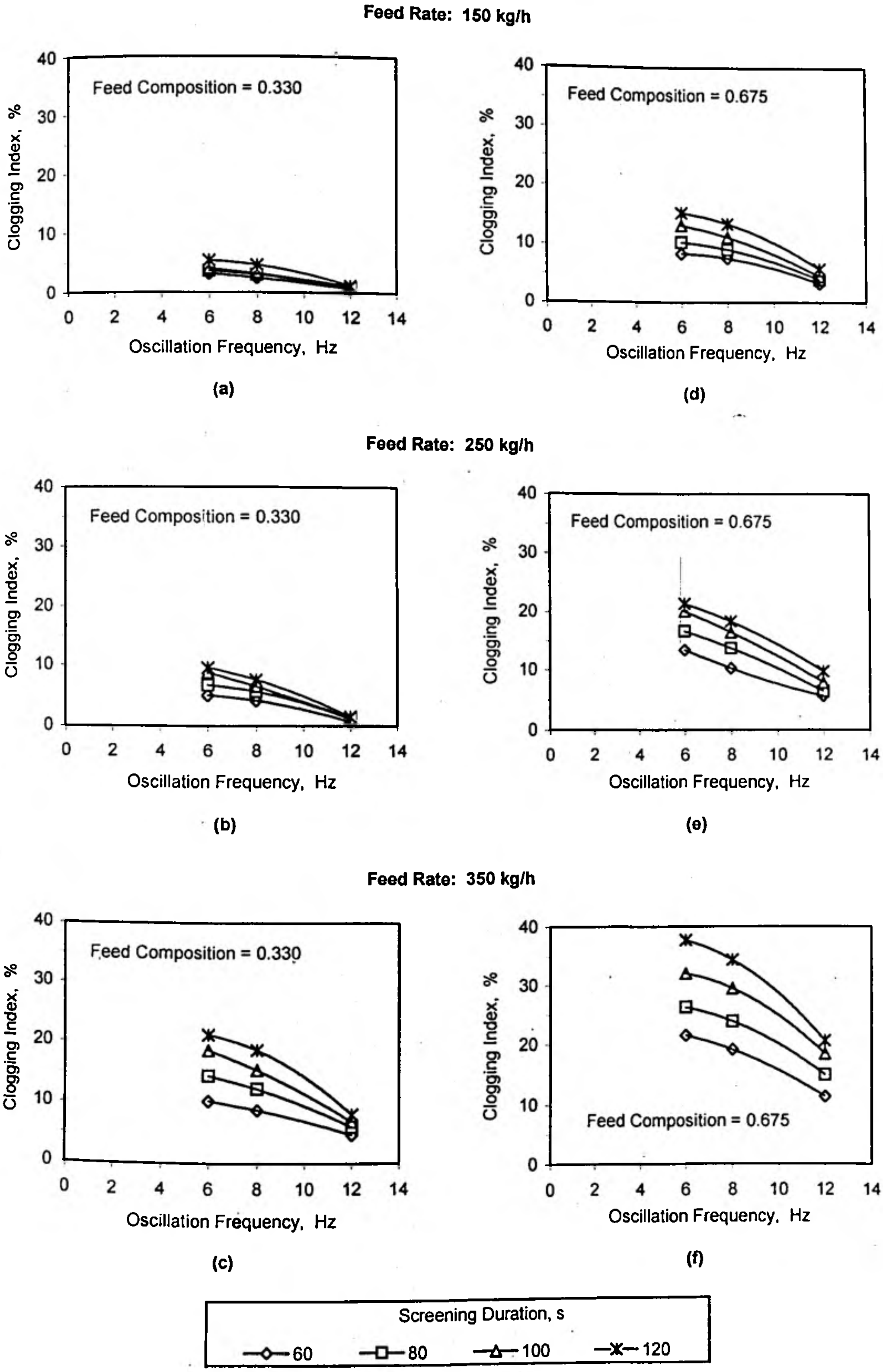


Fig. 5.6 **Effect of oscillation frequency on clogging index of an oscillating flat screen over a range of screening durations, feed rates and feed compositions**

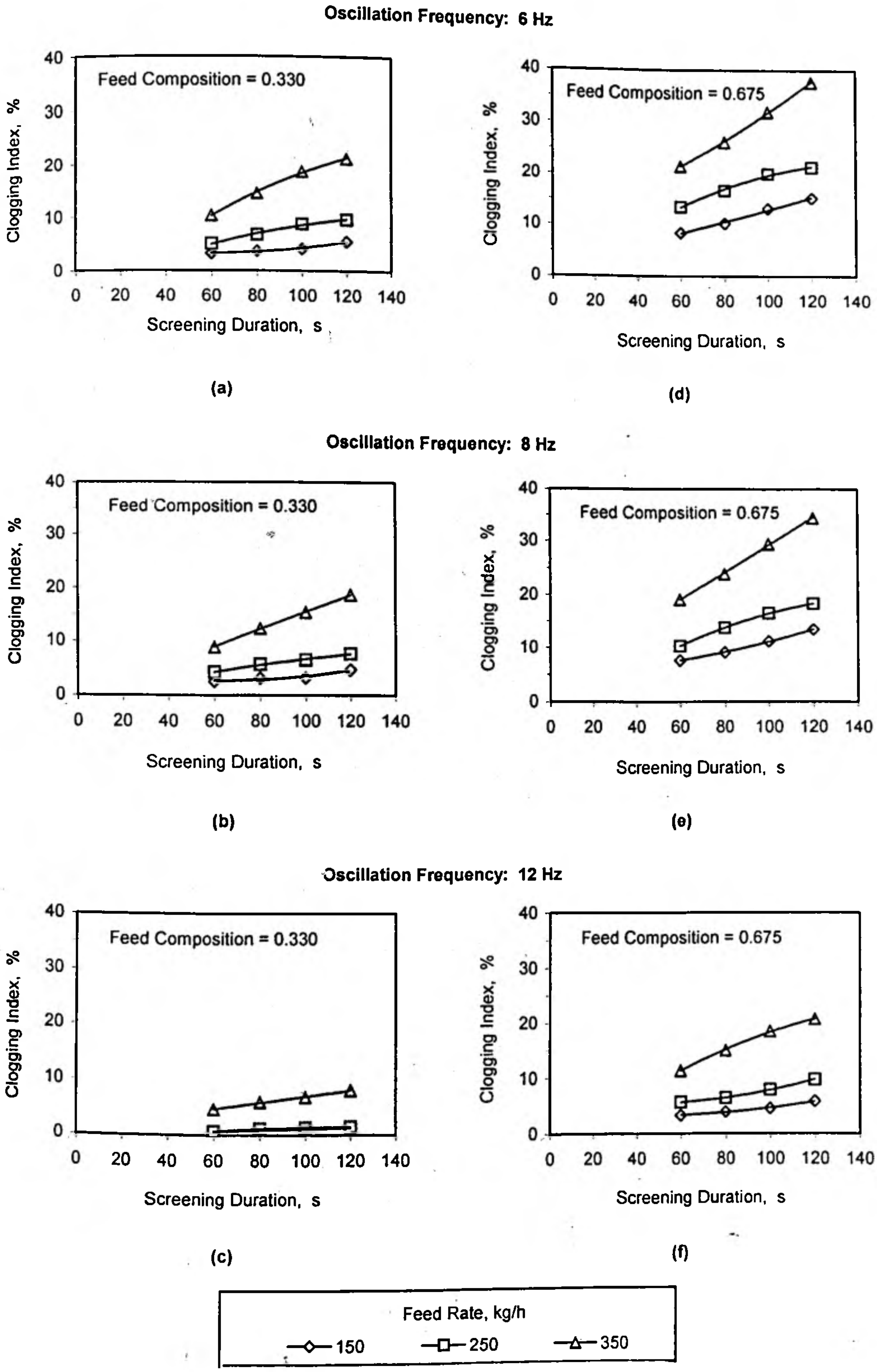


Fig. 5.7 **Effect of screening duration on clogging index of an oscillating flat screen over a range of feed rates, oscillation frequencies and feed compositions**

5.4.2.2 Effect of feed rate

The result of ANOVA presented in Table 5.7 indicates that the main effect of feed rate was second to only the feed composition. As with feed composition, this too was because of the variation effected in the number of oversize particles present on the screen surface at any instant. It is seen from Table C-3 and Fig. 5.5 that clogging index was directly proportional to the feed rate at different levels of feed composition, oscillation frequency, and screening duration. A second-degree polynomial equation of the following form best represented the relationship between the two with a high correlation coefficient.

$$C_i = a_0 + a_1 F_T + a_2 F_T^{\ 2} \qquad \ldots(5.6)$$

where C_i = clogging index, %;
F_T = feed rate, kg/h; and
a_0, a_1, and a_2 = constants.

At low feed rates, the population of berries on the screen was not dense and hence the particles could freely move on the surface. This aided in freely and easily lifting and moving out a trapped particle from an aperture due to the inertia forces; *i.e.*, there was no particle in the immediate proximity to offer a resistance to its upward movement and, thereafter, to its lateral displacement. Besides, the free rolling and/or sliding of an adjacent particle sometimes helped in dislodging a trapped particle from the aperture through inter-particle collision. But, at times, inter-particle collision can be detrimental to the dislodging of trapped particle from the aperture. The collision causes a trapped particle to settle deeper in the aperture. At the same time, higher feed rates caused both the clogging index and the screening inaccuracy to go up considerably. One reason for the higher clogging index was the presence of larger number of oversize particles. Another was the too close-location of particles, which caused the inter-particle collisions to occur more frequently; *i.e.*, at shorter intervals. Similarly, the amplitude of particle motion in a cycle was also made shorter by the adjacent particle. These prevented the dislodging of trapped particles from the perforations. The values of clogging index were, in general, maximum at the feed rate of 350 kg/h and minimum at 150 kg/h. Hence, as with the screening inaccuracy, there was a need to limit the amount of black pepper on the screen. Rose (1977) also made a similar observation. The feed rate used by Feller *et al.* (1986);

i.e., 986 kg/h for 1 m^2 of screen surface; appeared to be unfavourable for the black pepper; could be due to its wrinkled surface. A surface of this nature forces the berry to get firmly interlocked with the edge of the aperture in which it is trapped. Normal screen and particle motions do not dislodge it. So, when the feed rate was high, more of such berries entered the apertures and remained trapped. Hence, from a view of solely the clogging index, it is advisable to use the present screen at the feed rate of about 150 kg/h. But, since the ultimate objective of a screening process is not to achieve a certain clogging index, attention should be to achieve the required screening accuracy.

5.4.2.3 Effect of oscillation frequency

The result of ANOVA shows that the main effect of oscillation frequency too was significant at 1 per cent level, though not as high as that of feed composition and feed rate (Table 5.7). Besides, the results presented in Table C-3 and Fig. 5.6 indicate that clogging index was inversely proportional to oscillation frequency at different levels of feed composition, feed rate, and screening duration. The relationship between the two was best expressed by a second-degree polynomial equation of the following form with a high correlation coefficient.

$$C_i = a_0 + a_1 O_{fr} + a_2 O_{fr}^2 \qquad ...(5.7)$$

where C_i = clogging index, %;
O_{fr} = oscillation frequency, Hz; and
a_0, a_1, and a_2 = constants.

At the lowest frequency of 6 Hz, the inertia force was not large enough to drive out most of the particles seated in the apertures. This led to having more number of clogged apertures. Conversely, at the highest frequency of 12 Hz, the enhanced inertia force had the power to drive out a larger number of particles that clogged or tended to clog the apertures. This caused a reduction in the number of apertures remaining clogged. However, the frequency of oscillation could not be increased beyond a certain limit as it adversely affected the particle passage through the apertures. Feller (1980) reported that though clogging got totally eliminated at a frequency of 8.83 Hz, when testing for cotton seeds, the passage rate of undersize seeds was very low. In this study, even the frequency, 12 Hz, did not eliminate clogging. It could be due to the deeper settling of berries and the interlocking of their wrinkled surface with the edge of aperture.

5.4.2.4 Effect of screening duration

As indicated by the result of ANOVA, the main effect of screening duration was the least of the four parameters (Table 5.7). One reason for this might be the short duration selected in the study. The response of clogging index to screening duration at different levels of feed composition, feed rate, and oscillation frequency is illustrated in Fig. 5.7 based on the data in Table C-3. A second-degree polynomial equation of the following form was found to best represent the relationship with a high correlation coefficient.

$$C_i = a_0 + a_1 T_s + a_2 T_s^2 \qquad \text{...(5.8)}$$

where C_i = clogging index, %;
T_s = screening duration, s; and
a_0, a_1, and a_2 = constants.

The clogging index was seen, in general, to increase with the passage of time over the entire range of levels selected. This trend was almost similar to that of screening inaccuracy. This indicated that the clogging was cumulative in the screen evaluated. This finding is in agreement with those of the earlier workers (English, 1974; Rose, 1977; Feller *et al.*, 1986). In screening, particles much larger than the apertures, even if trapped in the apertures, generally tend to move out of the apertures due to screen motion, steeper inclination of the screen, and/or inter-particle collision. Such particles do not cause cumulative clogging at an alarming rate. But, particles slightly larger than the apertures enter the apertures and remain deeply settled. Normal operating conditions, which favour particle passage, often fail to dislodge such trapped particles from their seat in the apertures. Therefore, these particles become the agents chiefly responsible for cumulative clogging. In a continuous feed system, as more and more of such particles enter the screen surface with the lengthening of screening duration, the number of apertures getting clogged increases cumulatively. Hence, the increase in clogging index with the increase in screening duration, as noted in this study, was mainly due to these reasons.

Further, Fig. 5.7 shows that the rate of clogging was much higher for the feed composition of 0.675 than 0.330 at all the four screening durations. Similarly, it was higher also at higher feed rates. This was due to the presence of more quantity of oversize material on the screen surface. At the same time, the oscillation frequencies that produced higher clogging indices, even at prolonged screening durations, were the lower frequencies. As stated earlier, the inertia forces produced at these frequencies were often inadequate to drive out the trapped particles from the apertures. Thus, the overall effect was to increase clogging index with the passage of time. It is to mitigate this problem to some extent that the oscillating screens are stopped at some intervals and the particles manually removed from the apertures by tapping the screen element from below. In some cases, even devices like wire brushes, rollers, etc., moving beneath the screen surface, are used to physically lift the particles off their seats in the apertures (Feller et *al*., 1986).

5.4.2.5 Interaction effect

Treatment means for the 2-variable and 3-variable interaction effects found significant in the ANOVA are provided respectively in Tables 5.8 and 5.9. The interaction effects and the level of significance pertaining to the difference between any two treatments were investigated based on these means. The values of statistical least significant difference (LSD), for the levels of significance at 1 and 5 per cent, are also included in the tables. Non-significant differences are not observed between any two treatments among the entire 2-variable interactions. But, non-significant differences are seen in four cases of the 3-variable interaction (F_T x O_{fr} x T_s).

Two-variable interaction: Among the 2-variable interactions, the effect of feed rate, oscillation frequency, and screening duration, at all their respective levels, was to increase clogging index with the increase in level of feed composition from 0.330 to 0.675. As said before, an increase in the quantity of oversize particles increased clogging. Similarly, the effect of feed composition, at its both levels, was to increase clogging index with increase in the feed rate and the screening duration. The effect due to feed rate was also because of the increase in the quantity of oversize particles on the screen. The effect due to duration was related basically to the cumulative clogging. Therefore, lowest levels of these parameters were considered better in the operation of hexagonal trommels.

Table 5.8 Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, oscillation frequency, and screening duration, on clogging index of the oscillating flat screen

Feed Composition (F_C) (-)	Mean Clogging Index (C.), %										Mean
	Feed Rate (F_T), kg/h			Oscillation Frequency (O_{fr}), Hz			Screening Duration (T_S), s				
	150	250	350	6	8	12	60	80	100	120	
	%	%	%	%	%	%	%	%	%	%	%
0.330	2.82	4.88	12.15	9.28	7.72	2.85	4.47	5.99	7.33	8.67	6.62
0.675	8.81	13.32	24.13	19.67	17.22	9.37	11.17	13.90	17.00	19.61	15.42
Feed Rate (F_T), kg/h											
150	-	-	-	7.95	6.84	2.67	4.27	5.15	6.21	7.64	5.82
250	-	-	-	12.70	10.32	4.28	6.54	8.37	10.16	11.33	9.10
350	-	-	-	22.77	20.26	11.38	12.64	16.31	20.14	23.45	18.14
Oscillation Frequency (O_{fr}), Hz											
6	-	-	-	-	-	-	10.32	13.01	16.12	18.43	14.47
8	-	-	-	-	-	-	8.73	11.28	13.69	16.17	12.47
12	-	-	-	-	-	-	4.40	5.54	6.69	7.82	6.11
Mean	5.82	9.10	18.14	14.47	12.47	6.11	7.82	9.94	12.17	14.14	

LSD *for*	Significance Level 0.01	0.05
F_C	3.24	0.64
F_T	0.87	0.36
O_{fr}	0.87	0.36
T_s	0.65	0.34
$F_C \times F_T$	1.23	0.51
$F_C \times O_{fr}$	1.23	0.51
$F_C \times T_s$	0.92	0.48
$F_T \times O_{fr}$	0.81	0.46
$F_T \times T_s$	0.78	0.48
$O_{fr} \times T_6$	0.78	0.48

Table 5.9 Mean values showing 3-variable interaction effect, among feed rate, oscillation frequency, and screening duration, on clogging index of the oscillating flat tray screen

Feed Rate (F_T)	Mean Clogging Index (C_i), % — Oscillation Frequency (O_{fr}), Hz											
	6				8				12			
	Screening Duration (T_S), s				Screening Duration (T_S), s				Screening Duration (T_S), s			
	60	80	100	120	60	80	100	120	60	80	100	120
kg/h	%	%	%	%	%	%	%	%	%	%	%	%
150	5.82	7.00	8.62	10.37	5.03	6.08	7.18	9.05	1.97	2.37	2.82	3.52
250	9.23	11.68	14.42	15.47	7.20	9.67	11.47	12.93	3.18	3.77	4.60	5.58
350	15.92	20.35	25.33	29.47	13.97	18.10	22.43	26.53	8.05	10.48	12.65	14.35

LSD *for*	Significance Level 0.01	0.05
$F_T \times O_{fr} \times T_s$	1.62	0.92

At the same time, clogging index decreased with the increase in oscillation frequency at both the levels of feed composition. As mentioned earlier, the increase in screen acceleration forced out the particles trapped in the apertures. But, as seen earlier, higher frequencies were highly detrimental to particle passage.

The interaction between feed rate and oscillation frequency caused the clogging index to increase with the increase in feed rate at all the levels of frequency. The interaction between feed rate and screening duration also produced a similar trend. Contrary to this, the variation in clogging index with respect to the oscillation frequency at the different levels of feed rate showed a descending trend. It was due to the effect of increased screen acceleration. However, the trend was the reverse of this for the increase in screening duration at all the levels of feed rate.

The interaction between oscillation frequency and screening duration also raised the clogging index for the increase in screening duration at all the levels of frequency. It points again to the cumulative nature of clogging. But, the clogging index decreased with the increase in frequency at all the levels of duration. So, irrespective of the screening duration, increased acceleration helped in clearing clogged apertures.

Three-variable interaction: Among the 3-variable interactions, only that among feed rate, oscillation frequency, and screening duration was significant. All the levels of frequency and duration invariably raised the clogging index with the increase in feed rate, due to the increase in the number of oversize particles. Likewise, clogging index increased with the extension of screening duration at all the levels of feed rate and oscillation frequency. It confirmed again that clogging was cumulative with respect to time. But, the enhancement of oscillation frequency led to a reduction in clogging index at all the levels of feed rate and screening durations. This was also in tune with the 2-variable interactions. Though this was a beneficial condition, higher oscillation frequencies were disadvantageous for particle passage.

Based on the above, the set-up for obtaining the minimum clogging index is feed composition (0.330), feed rate (150 kg/h), oscillation frequency (12 Hz), and screening duration (60 s). However, the operation of an oscillating screen has to mainly take into consideration the requirements imposed by the grade quality; in other words, the screening inaccuracy. After taking this also into account, the major conclusions on the matter presented in this section (Section 5.4.2) on clogging index of oscillating flat screens are as follows.

1. Lower feed composition produced lower clogging index.
2. As an overall effect, the increasing of feed rate, and screening duration increased the clogging index.
3. Though the feed rate, 150 kg/h, was better than 250 and 350 kg/h for obtaining lower clogging indices, the feed rate 250 kg/h, was beneficial for achieving more accurate size grading.
4. The increasing of oscillation frequency reduced clogging.
5. Though the oscillation frequency, 12 Hz, was better than 6 and 8 Hz for obtaining lower clogging indices, the oscillation frequency of 8 Hz was advantageous for obtaining better size grading.
6. Clogging was cumulative with respect to screening duration.
7. Clearing of clogged apertures at intervals as short as 60 s improved sizing accuracy.

From the above, it was inferred that the existing oscillating flat screen in use was incapable of reducing the screening inaccuracy to the level of 5 per cent and below, as prescribed by the Agmark Grade Specification, in a single pass of the black pepper through the screen. In general, this is in agreement with the observations of many of the earlier workers that oscillating flat screens were inefficient in size classifying of particulate material (English, 1974; Rose, 1977; Feller *et al.*, 1986).

5.5 Prediction of Screening Inaccuracy of a Hexagonal Flighted-Trommel using a Semi-Empirical Model

Values of the screening inaccuracy of the three hexagonal flighted-trommels under study were predicted using Eqn (3.22) developed in this study. Sample calculations showing determination of the screening inaccuracy and the correction factors, C_o and C_u, in Eqn (3.22) are given in Appendix-D. The values of correction factors determined experimentally and substituted in Eqn (3.22) are presented in Appendix-D (Tables D-1 and D-2). Predicted values of screening inaccuracy are also included in Table D-2. A comparison between the values of screening inaccuracy predicted and observed has also been made, by determining the percentage deviation between the two, as presented in

Appendix-E (Table E-1). The observed values used in this comparison were those obtained from a separate set of experiments using the three trommels. Its data were those in Appendix-G (Table G-1). It indicates that the predicted and observed values were, in general, close to each other for the three trommels. Grand means of their percentage deviation; considering all three trommels; varied from –34.7 to 44.5 per cent. The variation was almost the same for all the trommels. This shows that the screening inaccuracy is predictable with reasonable accuracy using Eqn (3.22). Reasons for the accuracy could be the following.

1. The values of correction factors, C_o and C_u, are based on experimental results.
2. Transport of the berries in the axial direction of trommel took place almost at the rates, the values of which were determined theoretically.
3. The assumption that the sum of all deviations of berries from its cascade trajectory, due to inter-particle collisions and bounces, converges to zero is reasonable.

Validity of Eqn (3.22) was assessed also by finding the correlation between the predicted and the observed values for all the three trommels separately (Fig. 5.8). The coefficients of determination (R^2) were greater than 0.9 for all three trommels. It confirmed that values of the screening inaccuracy were predictable with reasonable accuracy using the proposed semi-empirical model. The relationships in all three cases were given by straight lines close to 45^0. It confirmed the validity of Eqn (3.22).

5.5.1 Prediction of correction factors, C_o and C_u, using Empirical Models

To develop empirical models for predicting the correction factors, C_o and C_u, for various factor-level combinations, multiple regression analyses were carried out separately for the three trommels. The data presented in Appendix-D (Table D-2) were utilised in the analyses. Regression models of the following forms well represented the relationship between correction factors and the various parameters under study. The models exhibited high values of coefficients of determination (R^2).

$$C_o = a_0 + a_1 F_T + a_2 N \qquad \text{...(5.9)}$$

$$C_u = a_0 + a_1 F_C + a_2 F_C^{\,2} + a_3 F_C F_T + a_4 F_T N \qquad \text{...(5.10)}$$

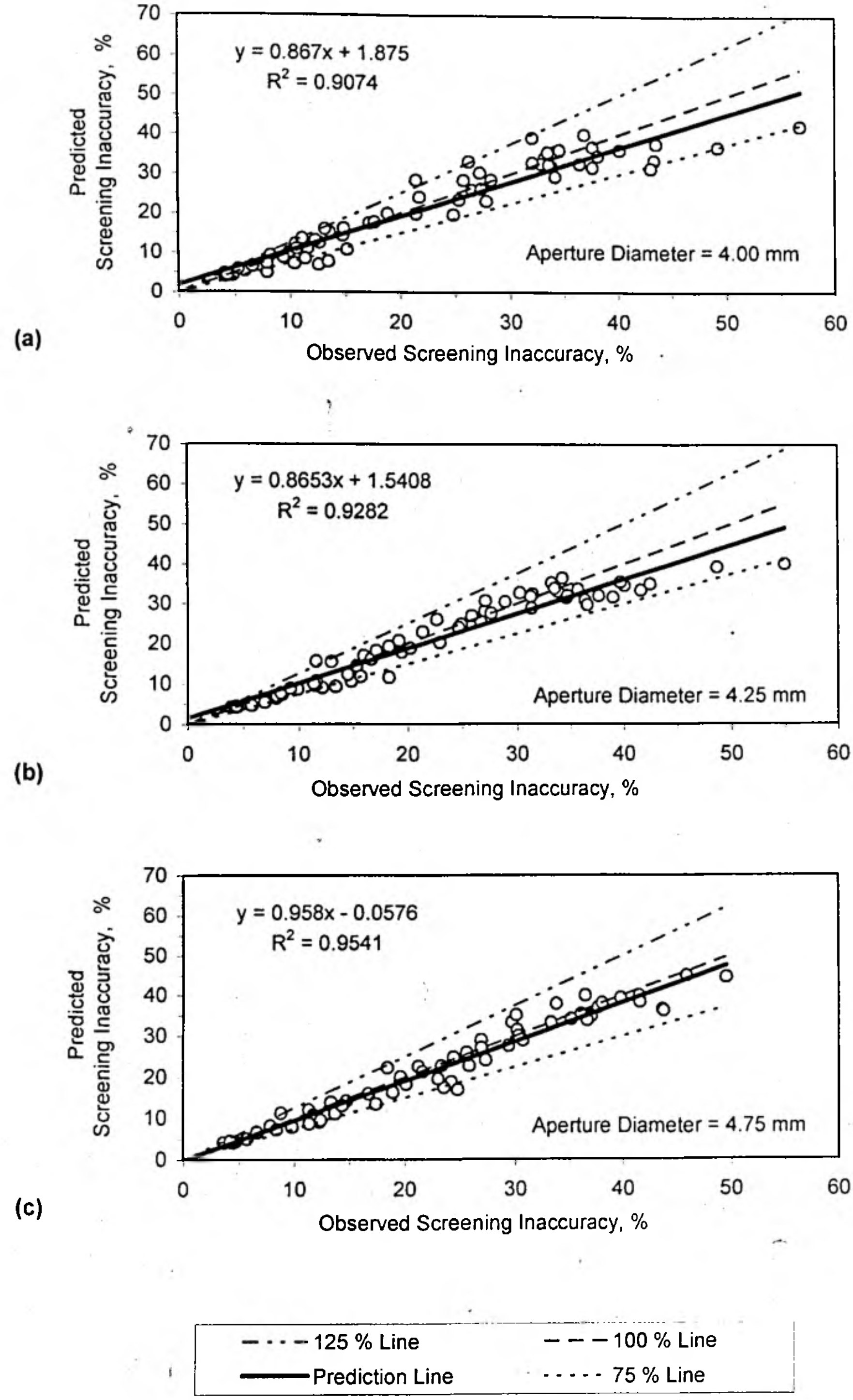


Fig. 5.8 Comparison of values of screening inaccuracy predicted by the semi-empirical model with those observed

where C_o = correction factor for non-ideality in screening oversize berries;
C_u = correction factor for non-ideality in screening undersize berries;
F_C = fraction of oversize berries in feed;
F_T = feed rate, kg/h;

N = trommel speed, r/min; and
a_0, a_1, a_2, a_3, and a_4 = constants.

The multiple regression models developed for the three trommels are given below.

1. For the trommel of 4.00-mm aperture diameter

$$C_o = 0.4057 + 0.00048F_T - 0.00211N \quad ...(5.11)$$
$$(R^2 = 0.93; \quad F = 92.35^{**})$$

$$C_u = -0.0337 + 0.3523F_C - 0.4704F_C^{\ 2} + 0.00062F_C F_T + 0.000013F_T N \quad ...(5.12)$$
$$(R^2 = 0.85; \quad F = 83.8^{**})$$

2. For the trommel of 4.25-mm aperture diameter

$$C_o = 0.4087 + 0.00042F_T - 0.00224N \quad ...(5.13)$$
$$(R^2 = 0.92; \quad F = 75.79^{**})$$

$$C_u = -0.0311 + 0.2939F_C - 0.4092F_C^{\ 2} + 0.00097F_C F_T + 0.000011F_T N \quad ...(5.14)$$
$$(R^2 = 0.89; \quad F = 113.28^{**})$$

3. For the trommel of 4.75-mm aperture diameter

$$C_o = 0.4034 + 0.00048F_T - 0.00219N \quad ...(5.15)$$
$$(R^2 = 0.93; \quad F = 86.36^{**})$$

$$C_u = -0.0338 + 0.3329F_C - 0.4454F_C^{\ 2} + 0.00081F_C F_T + 0.000014F_T N \quad ...(5.16)$$
$$(R^2 = 0.94; \quad F = 224.89^{**})$$

Based on the F-values, all the relationships are significant at 1 per cent level.

The values of correction factors, C_o and C_u, predicted using the empirical models, their corresponding observed values, and their percentage deviation are presented in Appendix-D (Tables D-3 and D-4) for all three trommels. The observed values were those obtained from a separate set of experiments and not those which formed the basis for empirical models. The data indicate that the two values are, in general, close to each other. Grand means of the percentage deviation of C_o; considering all the three trommels; lie in the range from –4.9 to 8.9 per cent. This small range could be because of the fewer factor combinations considered. The treatments were only 16 for a trommel; *i.e.*, four levels each of the feed rate and the trommel speed. The factor, feed composition, remained omitted since C_o was not applicable to a feed in the form of a mixture of both the oversize and the undersize berries. However, in respect of C_u, the deviations are larger and lie in the range from –25.3 to 26.6 per cent. Contrary to that of C_o, 64 treatments were under consideration. The additional factor taken into consideration was the feed composition. Therefore, just as feed composition brings about larger variations in screening inaccuracies and clogging indices, it might be causing similar deviations in the mixture hold-up in the trommel.

Besides, the correlation between the observed and the predicted values of correction factors, C_o and C_u, of the three trommels are shown in Figs. 5.9 and 5.10 respectively. The high values of coefficient of determination (R^2) suggest that, irrespective of the aperture diameter, the prediction of correction factors using the proposed empirical model would be reasonably accurate. The relationships in all three cases are given by straight lines close to 45^0. It confirmed the validity of Eqns (5.11) through (5.16).

5.6 Performance of a Hexagonal Flighted-Trommel

Investigations on the three hexagonal flighted-trommels for screening inaccuracy, zone-wise screening percentage of fines, clogging index, and power requirement yielded the following results.

5.6.1 Screening inaccuracy

Results of the experiments and the analyses of data, for determining the screening inaccuracies of the three trommels, are presented in Appendix-F (Tables F-1 through F-6). As stated earlier, the maximum screening inaccuracy tolerated by the Agmark Grade Specification is five per cent (Table 1.3). This was kept in view while making the analyses and the inferences. According to the ANOVA, based on the data in Tables F-1 through F-3, all the main effects and interaction effects of all the three parameters, *viz.*, feed composition, feed rate, and trommel speed are significant at one per cent level (Table 5.10). This is true for all the three trommels alike. Among the parameters, the main effect of feed composition is the most dominant; followed by the feed rate and the trommel speed in that order.

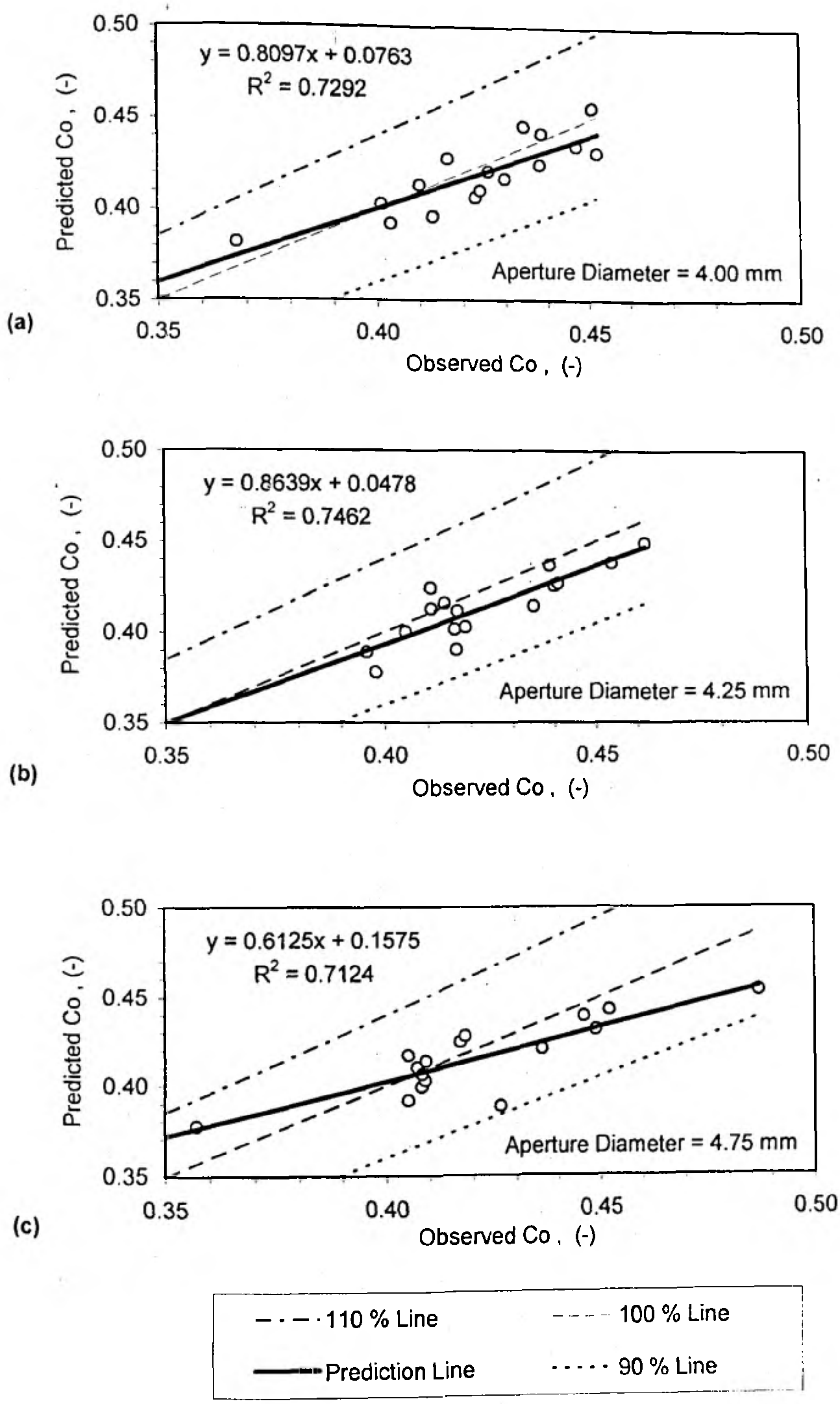


Fig. 5.9 Correlation between observed and predicted values of correction factor, C_o, in Eqn (3.22)

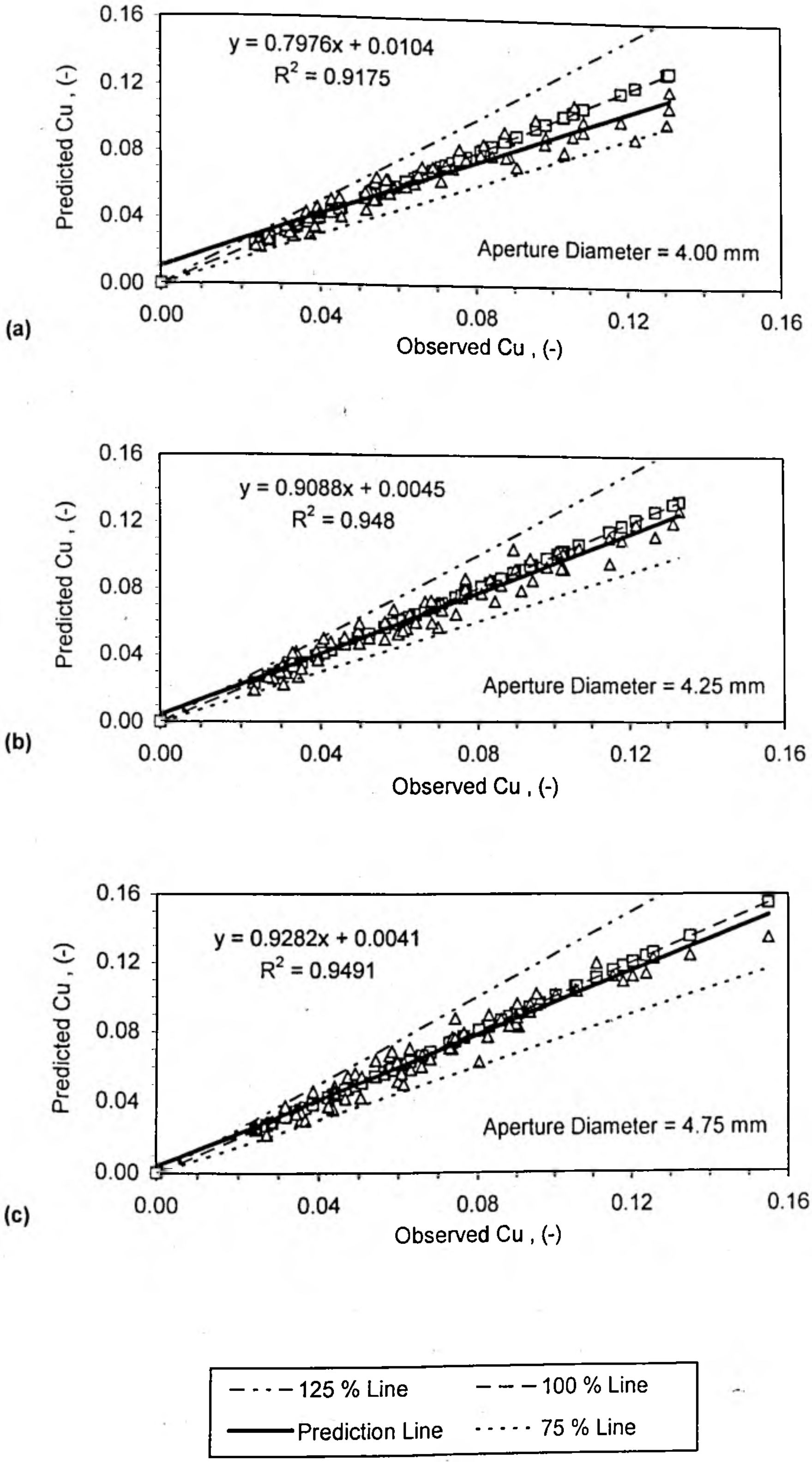


Fig. 5.10 **Correlation between observed and predicted values of correction factor, C_u, in Eqn (3.22)**

Table 5.10 Analyses of variance for the effect of feed composition, feed rate, and trommel speed on screening inaccuracy of trommels

Source of Variation	df	SS	MSS	F
		Aperture Diameter = 4.00 mm		
Feed Composition (F_C)	3	55812.60	18604.20	5648.49**
Feed Rate (F_T)	3	4397.43	1465.81	445.04**
Trommel Speed (N)	3	2050.97	683.66	207.57**
$F_C \times F_T$	9	547.88	60.88	18.48**
$F_C \times N$	9	181.04	20.12	6.11**
$F_T \times N$	9	184.35	20.48	6.22**
$F_C \times F_T \times N$	27	177.16	6.56	1.99**
Error	320	1053.97	3.29	
Total	383	64405.40		
		Aperture Diameter = 4.25 mm		
Feed Composition (F_C)	3	44130.88	14710.30	4771.95**
Feed Rate (F_T)	3	3711.87	1237.29	401.37**
Trommel Speed (N)	3	1481.60	493.87	160.21**
$F_C \times F_T$	9	266.66	29.63	9.61**
$F_C \times N$	9	205.14	22.79	7.39**
$F_T \times N$	9	105.77	11.75	3.81**
$F_C \times F_T \times N$	27	307.18	11.38	3.69**
Error	320	986.45	3.08	
Total	383	51195.55		
		Aperture Diameter = 4.75 mm		
Feed Composition (F_C)	3	47268.15	15756.05	5674.92**
Feed Rate (F_T)	3	5008.24	1669.41	601.28**
Trommel Speed (N)	3	967.30	322.43	116.13**
$F_C \times F_T$	9	325.92	36.21	13.04**
$F_C \times N$	9	72.41	8.05	2.90**
$F_T \times N$	9	80.68	8.96	3.23**
$F_C \times F_T \times N$	27	188.27	6.97	2.51**
Error	320	888.46	2.78	
Total	383	54799.41		

** Significant at 1 per cent level

The changes in screening inaccuracy, with respect to the changes in levels of these parameters relating to the trommel having apertures of 4.00 mm diameter, are depicted in the form of graphs too and discussed (Fig.s 5.11 through 5.13). Since the pattern of change is almost alike for the three trommels irrespective of the aperture size, the figures relating to the other two are not presented. The reason for the strong similarity could be the very narrow difference between the aperture sizes. The effects of these parameters on screening inaccuracy are discussed more in detail below.

5.6.1.1 Effect of feed composition

The four levels of feed compositions used in the experiments were 0.150, 0.325, 0.500 and 0.675. This indicated of the fraction of oversize berries in the feed by weight; *i.e.*, it is approximately one-sixth in the feed for a composition of 0.150 and one-third for 0.325. The strongest main effect of feed composition, shown by the ANOVA, is considered to be due to the large-scale changes it brings about in the number of undersize berries coming onto the screen surface. This could be causing large-scale variations in the screening inaccuracy. From the regression analyses, it was seen that a second-degree polynomial equation of the following form best represented the relationship between screening inaccuracy (S_i) and feed composition (F_C) with high values of correlation coefficient (R') over 0.97 for all the trommels.

$$S_i = a_0 + a_1 F_C + a_2 F_C^{\,2} \qquad \ldots(5.17)$$

It is seen from the data and Figure 5.11 that, in general, the increase in fraction of oversize material in the feedstock decreased screening inaccuracy appreciably. The result presented in Section 5.4.1.1 on oscillating flat screen is also in support of this. Further, the report of Standish *et al.* (1986) points to the beneficial effect of the presence of oversize material in the feed. According to them, the oversize material assisted the near-mesh particles in their passage through the apertures. This appears to be due to the impact caused on the near-mesh particle by the heavier oversize berries when they moved on the inside surface of the trommel element. It caused the near-mesh particles to be forced through the apertures at a faster rate. In a separate study too, Standish (1985) detected that the presence of oversize particles in the feed enhanced the sieving rate dramatically.

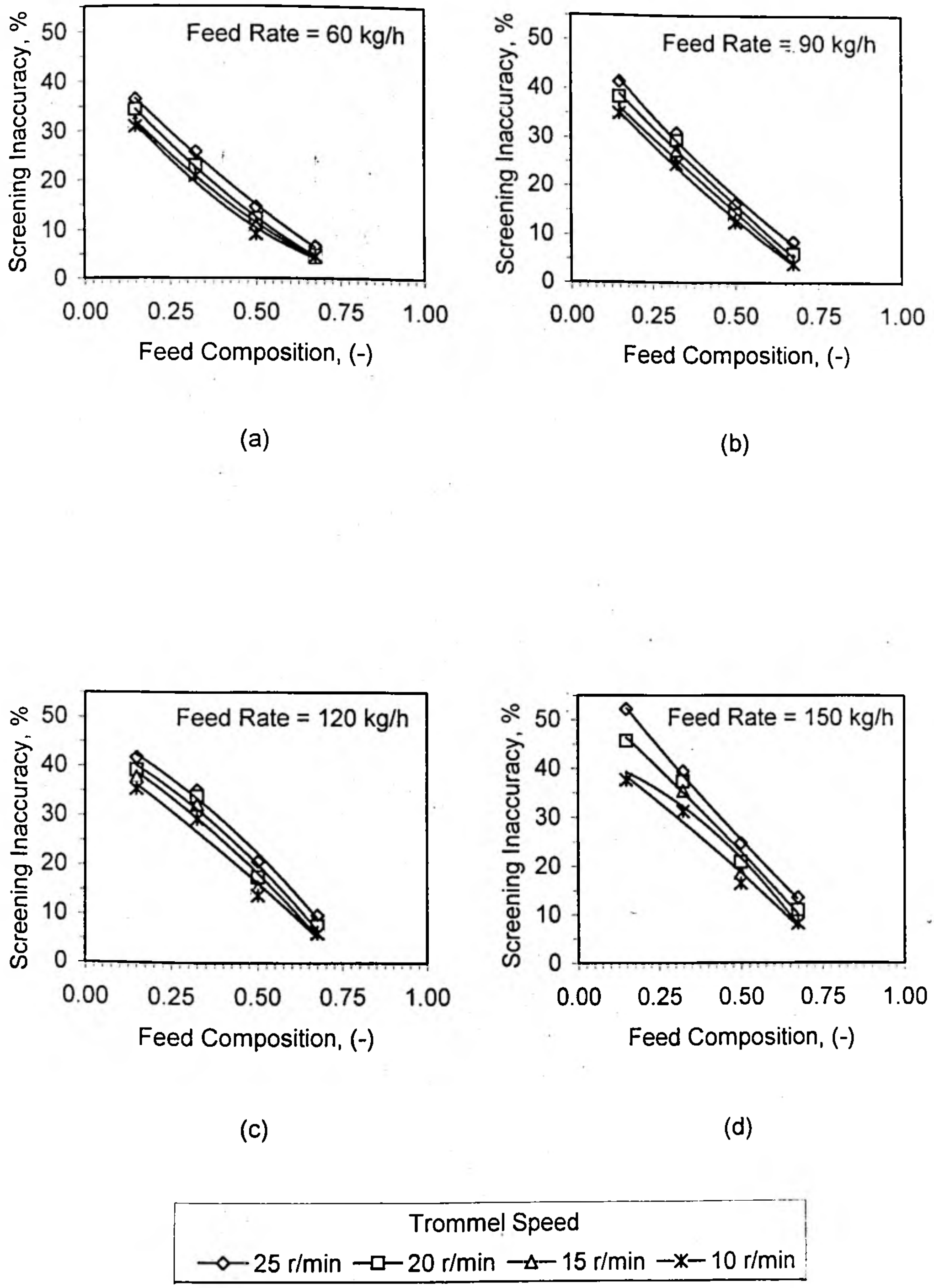


Fig. 5.11 Effect of feed composition on screening inaccuracy of the trommel of 4.00-mm aperture diameter at different trommel speeds and feed rates

Another reason for the lowering of screening inaccuracy could be, as observed in the present study, the reduction in the number of fines competing for access to the definite number of apertures and the resultant reduction in the number of particles becoming unsuccessful in passing through the apertures.

The trend shows that the rate of reduction in screening inaccuracy was steeper in the intermediate range between the feed composition of 0.325 and 0.500. In the presence of a larger number of undersize particles in the feedstock, at the feed compositions of 0.150 and 0.325, the frequency of scanning of an undersize particle by the apertures was considerably reduced. As a result, screening accuracy remained at a higher level. With the increase in feed composition to 0.500, the number of undersize particles in the feed was reduced. It enabled the scanning of such particles more frequently by the apertures and consequently a larger number became successful in passing through the apertures. However, as the feed composition was increased further, though there was a reduction in screening inaccuracy to the desired levels, the rate of reduction was not steeper. This indicates that, in the presence of too many oversize berries, all the undersize berries were not allowed to pass through the apertures. The overpopulation of oversize berries could be hindering the passage of some of the undersize berries. As a result, the rate of reduction in screening inaccuracy became slower.

It is also observed that, at the feed composition of 0.15 and 0.325, the sizing was so inaccurate that the turn out of fines in tailings was, in general, well over 20 per cent. At the same time, the black pepper feedstock, coming from the farms after harvest, is nearly of a composition of this nature. The quantity of undersize berries is much more than that of the oversize material. Therefore, hexagonal flighted-trommels were less effective in the accurate sizing of black pepper freshly collected from the field. However, an initial quick scalping of the black pepper freshly collected from the field, in a slotted element screen or an oscillating flat screen reduced the percentage of undersize material in the feedstock to nearly 35 percent or lower. The screening of such a material in the hexagonal flighted-trommel gave lower screening inaccuracies comparable with that obtained in the case of feed composition of 0.500 and 0.675. The undersize turn out in tailings was observed to be generally lower than 10 percent at the feed composition of 0.675. At trommel speeds ranging from 10 to 20 r/min and feed rates from 60 to 90 kg/h the trommels gave screening inaccuracies even lower than five per cent. This confirmed that, with a feedstock that has undergone initial scalping, the hexagonal flighted-trommel is capable of giving screening inaccuracies in the range tolerated by Agmark Grade Specifications. It was also found that increased presence of oversize material, up to a certain level, aided in facilitating the passage of fines through apertures.

5.6.1.2 Effect of feed rate

The feed rates selected were 60, 90, 120 and 150 kg/h. The result of ANOVA shows that the main effect of feed rate was highly significant for all the trommels, though not to the level of feed composition (Table 5.10). However, it was more than that of the trommel speed. This was partly due to the changes it effected in the total number of undersize and oversize particles reaching the screen surface at any instant. Since the number of apertures was fixed, only a limited number of fines, irrespective of their total number on the screen, could succeed in getting sifted. The rest moved out as tails. So, the variation in feed rate (F_T) induced changes in screening inaccuracy (Si). The relationship between them was best represented by a second-degree polynomial equation of the following form with a high correlation coefficient.

$$S_i = a_0 + a_1 F_T + a_2 F_T^{\ 2} \qquad \text{...(5.18)}$$

The relationship between the two is also presented with the aid of graphs in Fig. 5.12. As stated, it is of the trommel having apertures of 4.00 mm diameter. The general trend was for the screening inaccuracy to increase with the feed rate. The result presented in Section 5.4.1.2 on oscillating flat screen is also in support of this. Similar observations are seen made also by Fowler and Lim (1959), Rose (1977), and Feller *et al.* (1986). The reasons for this type of an effect were those already stated above. In addition to that, a factor that mainly controlled the bed thickness of berries in the trommel was the feed rate. Also, it regulated population of berries in unit area. Smaller population densities, occurring at lower feed rates, provided larger inter-particle space. It permitted free movement of berries without frequent inter-particle collision. As a result, an undersize particle could get sifted without much hindrance from its neighbours, provided the screen motion and other factors favoured it. This led to smaller screening inaccuracies at lower feed rates.

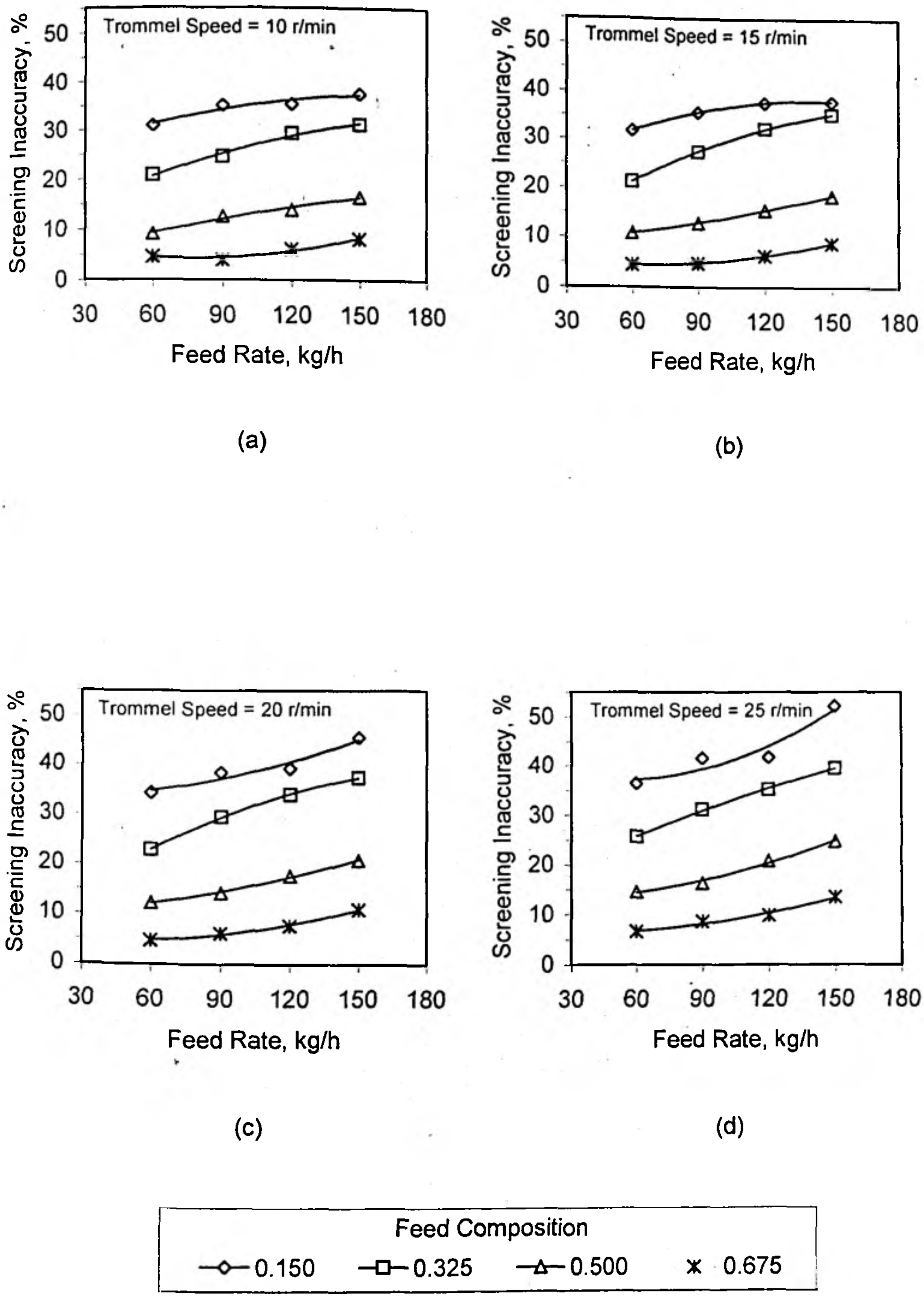


Fig. 5.12 Effect of feed rate on screening inaccuracy of the trommel of 4.00-mm aperture diameter at different feed compositions and trommel speeds

Screening inaccuracies, below five per cent, were obtained at the feed rates of 60 and 90 kg/h. It is noted that the curves tend to become flatter upon reducing the feed rate from 90 to 60 kg/h. This trend is more relevant for a feed of higher composition; *i.e.*, when less quantity of undersize material remains on the screen surface. It indicates that appreciable advantage cannot be derived by reducing the feed rate any further and instead, the factor to be changed for lowering the screening inaccuracy is the composition of feed. In some cases, it is noted that the screening inaccuracy decreases when the feed rate is increased. As this phenomenon is not of a frequent occurrence and as the margin of difference is too small, it is considered to be stray cases. No specific reason for the same could be detected. Based on the above, the feed rates acceptable for obtaining lower percentage of fines in tailings are 60 and 90 kg/h irrespective of the aperture diameter.

5.6.1.3 Effect of trommel speed

The trommel speeds used in the study were 10, 15, 20, and 25 r/min. The result of ANOVA presented in Table 5.10 shows that the main and the interaction effects of trommel speed were significant even at 1 per cent level. It reveals also that the trommel speed, within the range studied, exerted only the least effect compared to the feed rate and the feed composition. This could be because, within the levels selected, the effect exerted by the changes in peripheral velocities of the trommel was not as much as that by the changes in the number of undersize particles fed to the screen. The relationship between screening inaccuracy (S_i) and trommel speed (N), established through regression analyses, was best represented by a second-degree polynomial equation of the following form with a high correlation coefficient.

$$S_i = a_0 + a_1 N + a_2 N^2 \qquad \text{...(5.19)}$$

The response of screening inaccuracy to the trommel speed is illustrated in Fig.5.13. The general trend for the screening inaccuracy was to increase with the speed. Also, the result presented in Section 5.4.1.3 on oscillating flat screen support this, though the motion in one was rotation and the other oscillation. This agreed also with the observations of some of the earlier researchers (Fowler and Lim, 1959; Garvie, 1966; Feller et al., 1986; and Bosoi et al., 1990), though their studies too were on oscillating or vibrating screens.

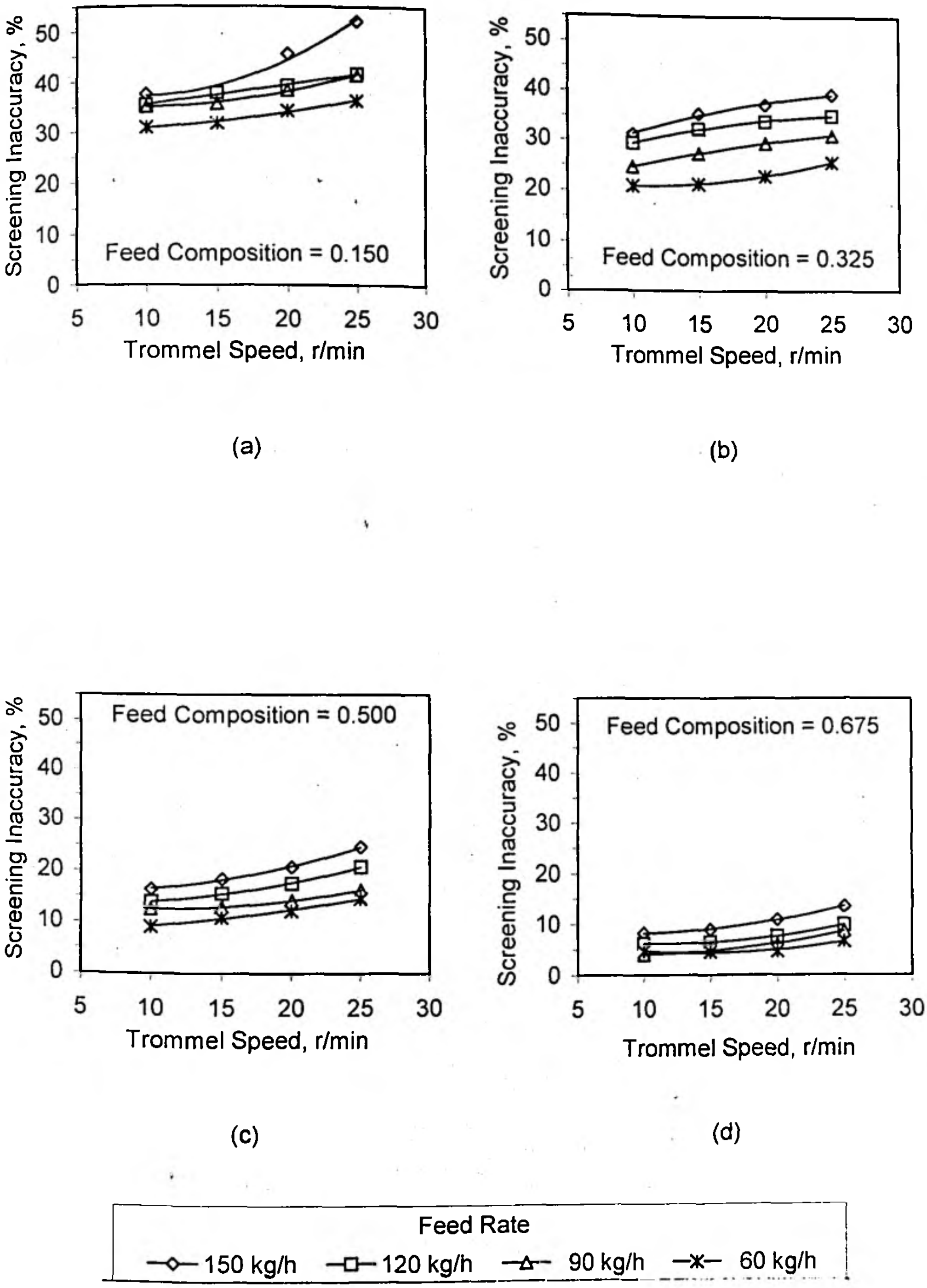


Fig. 5.13 Effect of trommel speed on screening inaccuracy of the trommel of 4.00-mm aperture diameter at different feed rates and feed compositions

In the present study, at the lower feed rates and higher feed compositions, the trend was reverse in certain cases. It confirmed again of the beneficial effect of smaller quantity of undersize material on the screen surface. In these cases, screening inaccuracy was the lowest at 15 r/min, i.e., between the levels, 10 and 20 r/min. It indicated that peripheral velocities above 0.21 m/s and below 0.1 m/s at the radius of hexagonal flighted-trommel, and above 0.18 m/s and below 0.09 m/s at the apothem reduced black pepper passage through the apertures. The higher screening inaccuracies at higher peripheral velocities was chiefly due to the skipping of perforations by the particles. At these velocities, the particle moved faster and the momentum prevented them from falling into the perforations. This was more pronounced for a near-mesh particle than a very small particle. Besides, at higher velocities, sufficient time was also not allowed to a particle to fall into the aperture and pass through it. The result was an increase in screening inaccuracy. From the angle of capacity, it is desirable that the screen be operated at higher speeds. But, this could not be done due to the reasons cited above. The maximum permissible velocity would have been still lower had lifters or flights been not provided at the six corners of the trommels. These flights served as obstacles to the quicker movement of material along screen's inner surface and across the trommel axis. Besides, black pepper being more spherical in shape, as indicated by the high sphericity, tended to roll faster on the screen surface in the absence of any hurdle. The flights hindered this also. In the process, the particle was prevented from accelerating to undesirable levels. This prevented skipping of apertures and allowed more time for the particle to fall into the aperture and pass through it. Hence, a trommel with internal flights might tolerate slightly higher speeds than the one without flights, but not above the limits given above. If it exceeded these limits, the flights too would become ineffective. At lower peripheral velocities corresponding to 10 and 15 r/min, the tendency of the particle to skip over the holes, while sliding and/or rolling, was considerably reduced. As a result, the frequency of scanning of a particle by the apertures increased. This allowed a particle to present itself to the apertures more times; but each time, perhaps, with a different orientation. This might help the particle to enter the aperture, at least on one occasion, with its second dimension perpendicular to the longitudinal axis of the aperture. If the inertia force exerted by the edge of the aperture was not adverse, the particle would succeed in gaining passage through the aperture. At the same time, if the quantity of undersize particles on the screen is larger due to higher feed rates or feed compositions, even a peripheral velocity corresponding to 10 r/min would not be very effective. As stated earlier, a particle is scanned fewer times if more number of undersize particles remained on the screen. The success of any screening process depends also upon the frequency of scanning of particles by the apertures. The level of screening inaccuracies tolerated by the Agmark Grade Specifications is seen attained by all the three trommels at the speeds, 10 and 15 r/min, and feed rates, 60 and 90 kg/h, but only at the feed composition of 0.675.

5.6.1.4 Interaction effect

The ANOVA indicated that the entire 2-variable and 3-variable interactions were significant at 1 per cent level for all the three trommels (Table 5.10). The treatment means showing the effects of these interactions relating to the trommel of 4.00-mm apertures are furnished in Tables 5.11 and 5.12, and those relating to the other two trommels are given in Appendix-H (Tables H-1 through H-4). The level of significance pertaining to the difference between any two treatments is observable from these means. The values of statistical least significant difference (LSD), for the levels of significance at 1 and 5 per cent, are also furnished along with the tables.

Two-variable interaction: It is seen that the variations in treatment means relating to the feed composition at any level of the feed rate and trommel speed were significant at 1 per cent level. Besides, for the three trommels, the screening inaccuracy reduced with the increase in feed composition at all the levels of feed rate and trommel speed. As the feed composition was varied, it changed the amount of undersize particles on the screen surface. More amount of them on the screen, at any instant, enhanced the screening inaccuracy. This calls for initial scalping of the feedstock before being fed to the trommels. Similarly, the increase in feed rate increased the screening inaccuracy, at all the levels of feed composition, for the trommels of 4.00- and 4.75-mm apertures. But, an exception was observed in the case of trommel of 4.25-mm apertures for the increase in feed rate from 60 to 90 kg/h at the feed composition of 0.150. However, the reduction in screening inaccuracy was non-significant as shown by the LSD values.

Table 5.11 Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, and trommel speed, on screening inaccuracy of the trommel of 4.00-mm apertures

Feed Composition (F_C) (-)	Mean Screening Inaccuracy, %								
	Feed Rate (F_T), kg/h				Trommel Speed (N), r/min				Mean
	60	90	120	150	10	15	20	25	
0.150	33.35	37.68	38.50	43.39	34.76	35.85	39.37	42.95	38.23
0.325	22.65	28.12	32.66	35.82	26.47	29.10	30.87	32.80	29.81
0.500	11.67	13.98	16.98	20.13	13.02	14.45	16.19	19.10	15.69
0.675	5.09	5.87	7.44	10.38	5.69	6.13	7.32	9.63	7.19
Feed Rate (F_T), kg/h									
60	-	-	-	-	16.33	17.10	18.52	20.80	18.19
90	-	-	-	-	19.05	20.19	22.03	24.38	21.41
120	-	-	-	-	21.17	23.01	24.55	26.85	23.90
150	-	-	-	-	23.40	25.22	28.65	32.45	27.43
Mean	18.19	21.41	23.89	27.43	19.99	21.38	23.44	26.12	

Significance Level	LSD *for*					
	F_C	F_T	N	$F_C \times F_T$	$F_C \times N$	$F_T \times N$
0.01	0.84	0.84	0.84	1.05	1.05	1.05
0.05	0.44	0.44	0.44	0.88	0.88	0 88

Table 5.12 Mean values showing 3-variable interaction effect, among feed composition, feed rate, and trommel speed, on screening inaccuracy of the trommel of 4.00-mm apertures

Feed Rate (F_T) kg/h	Mean Screening Inaccuracy, %															
	Feed Composition (F_C), (-)															
	0.150				0.325				0.500				0.675			
	Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min			
	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	30.92	31.80	34.32	36.38	20.77	21.28	22.88	25.65	9.07	10.87	12.15	14.58	4.55	4 47	4 73	6 60
90	35.12	35.73	38.35	41.53	24.55	27.38	29.45	31.10	12.58	12.85	14.23	16.27	3.97	4.78	6.08	8.63
120	35.38	37.78	39.18	41.67	29.33	32.33	33.87	35.10	13.90	15.58	17.60	20.83	6.05	6.35	7.55	9 80
150	37.62	38.07	45.63	52.23	31.23	35.40	37.27	39.37	16.53	18.48	20.78	24.73	8.20	8.93	10.92	13.48

Significance Level	LSD *for*
	$F_C \times F_T \times N$
0.01	1.83
0.05	1.26

The increase in trommel speed too, increased the screening inaccuracy at all the levels of feed composition for the three trommels. The enhanced inertia forces at higher speeds were responsible for this. Besides, the particles were not allowed adequate time to sink into the apertures and pass through it.

In addition to this, the increase in trommel speed at the various levels of feed rate raised the screening inaccuracy too of the three trommels. The effect of feed rate at all the levels of trommel speed was alike. Therefore, no specific advantage was derived in increasing either the feed rate or the trommel speed.

Three-variable interaction: The treatment means furnished in Table 5.12 and Appendix-H (Tables H-3 and H-4) were used in analysing the 3-variable interaction of the three trommels. A comparison with the LSD values show that the differences in treatment means were significant at 1 per cent level for all changes in the level of feed composition. The effect of interaction, at any level of the feed rate and the trommel speed, was to considerably lower the screening inaccuracy when the feed composition increased in its level. Screening inaccuracies, in the range desired by the Agmark Grade Specifications, were produced at the highest feed compositions. Further, the augmentation of feed rate generally increased screening inaccuracy at all the levels of feed composition and trommel speed. But, LSD values show that the difference between two treatment means was non-significant for 27 of the 144 changes in the level of feed rate concerning the three trommels. The lowest inaccuracies were at the fed rate of either 60 or 90kg/h for the three trommels. It was seen that the second feed rate of 90 kg/h was capable of giving the screening inaccuracies tolerated by the Agmark Grade Specifications. Further, the increase in trommel speed generally increased screening inaccuracy at all the levels of feed composition and feed rate. However, the difference between two treatment means was non-significant in as many as 53 of the total number of 144 changes in the levels of speed; all trommels taken together. Many of these were for the change in speed from 10 to 15 r/min. As stated earlier, the speeds were quite close to each other. So, the change in relative velocity between the screen surface and the particles was not large enough to produce substantial changes in screening inaccuracies.

Based on the above it is concluded that, the 2- and 3-variable interactions favoured particle passage and produced lower screening inaccuracies, particularly at the two lower levels of the feed rate and the trommel speed (60 and 90 kg/h, and 10 and 15 r/min respectively) and at the lowest level of feed composition (0.675).

Taking into account all that are presented in this section (Section 5.6.1) on screening inaccuracy of hexagonal flighted-trommels, the major conclusions are as follows.

1. The screening inaccuracy decreased with the increase in feed composition.
2. The feed composition, 0.675, produced screening inaccuracies of the order tolerated by the Agmark Grade Specifications.
3. As an overall effect, increasing of the feed rate and the trommel speed was deleterious to accurate size classifying because their increase raised the screening inaccuracy, especially at their higher levels.
4. The lower feed rates, 60 and 90 kg/h, were better than 120 and 150 kg/h for obtaining lower screening inaccuracies. They produced screening inaccuracies below 5 per cent.
5. The trommel speeds, 10 and 15 r/min, were better than 20 and 25 r/min for obtaining lower screening inaccuracies. Screening inaccuracies lower than five percent were produced at these speeds.
6. The trommels were incapable of reducing the screening inaccuracy to the levels tolerated by the Agmark Grade Specifications, in size classifying black pepper of feed compositions lower than about 0.675, in a single pass through the screen,
7. The trommel was capable of producing screening inaccuracies below 5 per cent for a black pepper feedstock, which had undergone an initial scalping.
8. These were equally applicable to the trommels of aperture diameters, 4.00, 4.25, and 4.75 mm, irrespective of their aperture size.

5.6.2 Zone-wise screening percentage of fines

The percentage of fines screened in a zone is the quantity of undersize particles passing through the apertures in that zone for a certain duration expressed as a percentage of the total quantity of undersize particles entering that zone along with the feedstock during that period. It was determined using Eqn (3.9). For the purpose, six zones - each of 15-cm length - were demarcated in the perforated portion along the length of trommel element. The zone closest to the inlet was taken as the first and the one nearest to the outlet the last. The berries sifted in each zone, for certain duration, was separately collected and weighed. The data are presented in Appendix-F (Tables F-4 through F-6). The percentages of fines sifted zone-wise of the three trommels are given in Table F-7.

The results show that, the zone-wise screening percentage generally decreased with the increase in the distance of the zone from the inlet. This is in agreement with the result obtained by Standish and Meta (1985). The trend observed is illustrated in Figs. 5.14 and 5.15. Since the data in Table F-7 indicate that the trend is more or less the same for the three trommels, the figures relating to only one trommel, *i.e.*, of 4.75-mm aperture, is presented here. It is seen from the tables and the figures that, generally, higher feed compositions (0.675 and 0.500) produced more screening percentage in the first zone compared to the lower feed compositions. The maximum values of screening percentage in the first zone for the trommels of aperture sizes, 4.00, 4.25, and 4.75 mm, were respectively 55.5, 53.5, and 49.5 per cent. All the three were for the feed composition of 0.675. The feed composition of 0.500 also gave values closer to these. Conversely, the feed composition of either 0.150 or 0.325 produced the minimum values. This shows that, if the quantity of undersize material in the feedstock exceeded a limit, the additional material remained mostly un-sifted and passed as overflow to the succeeding zone.

However, the trend was the reverse in the sixth zone. At higher feed compositions, the feedstock entering the last zone contained lesser quantity of undersize particles, which were too small for the apertures; *i.e*, it contained more of near-mesh particles; and this depressed the screening percentage. But, at lower feed compositions, the feedstock entering each zone contained more quantity of undersize material having large amount of particles, too small for the apertures. So, larger screening percentages were produced in all the six zones. But, the screening percentage never reached 100 per cent, when in the presence of oversize material. This could be due to the deleterious effect produced by the bigger particles. They appeared to be clogging the holes and preventing the undersize particles from being scanned by the apertures. Standish *et al.* (1986) pointed to the entanglement of fines by the oversize particles as the cause for reduction in screening percentage. All these could be the reasons for not attaining a screening percentage of 100 per cent or closer to in any of the zones at any of the feed compositions. The effect of feed rate too is discernible from the data and the figures. Higher feed rates, generally, produced lower screening percentages due to the enhancement in the total number of particles reaching the screen surface.

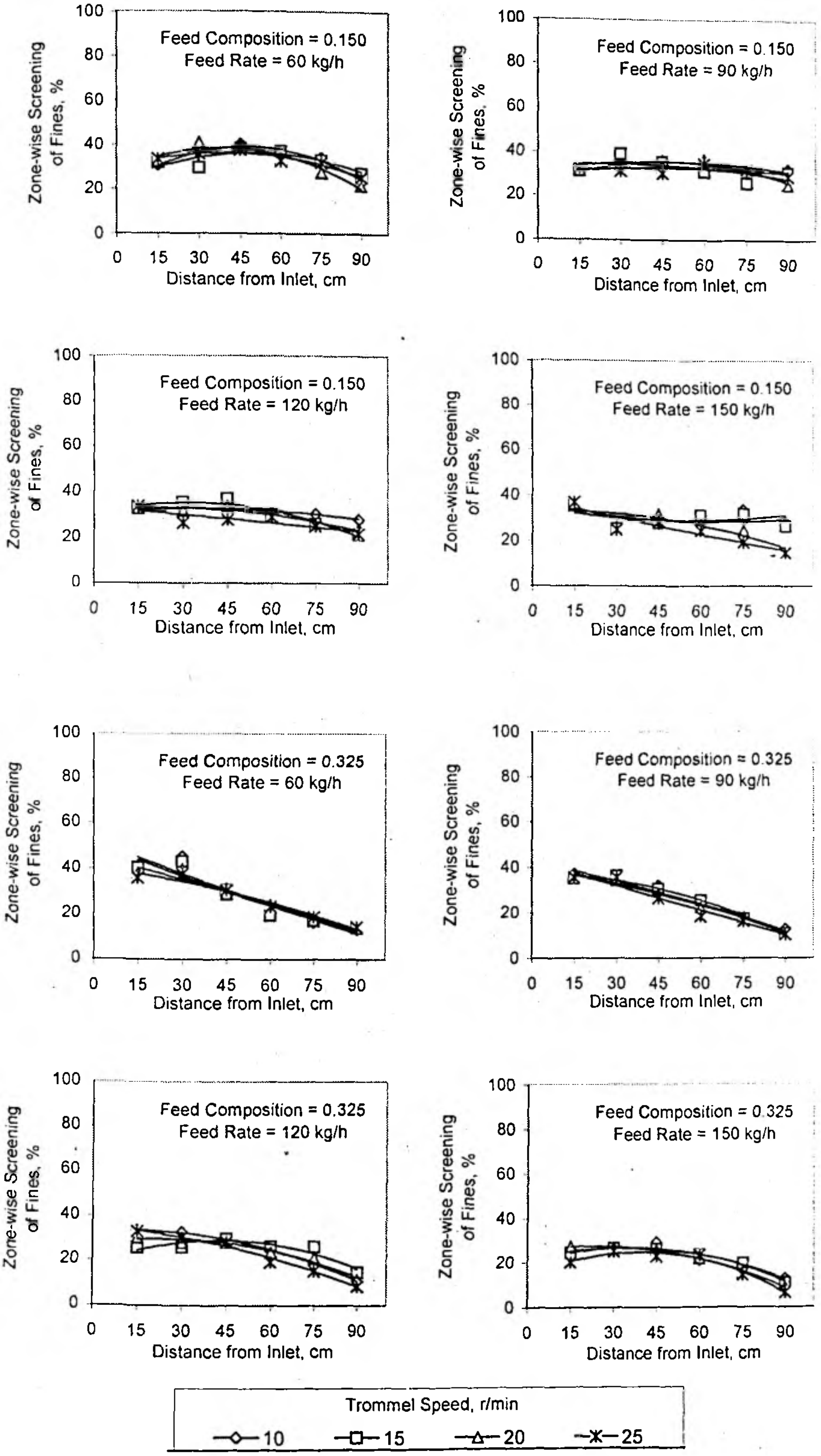


Fig. 5.14 Zone-wise screening percentage of fines at different trommel speeds, feed rates, and feed compositions (0.150 and 0.325) of the tromel of 4.75-mm apertures

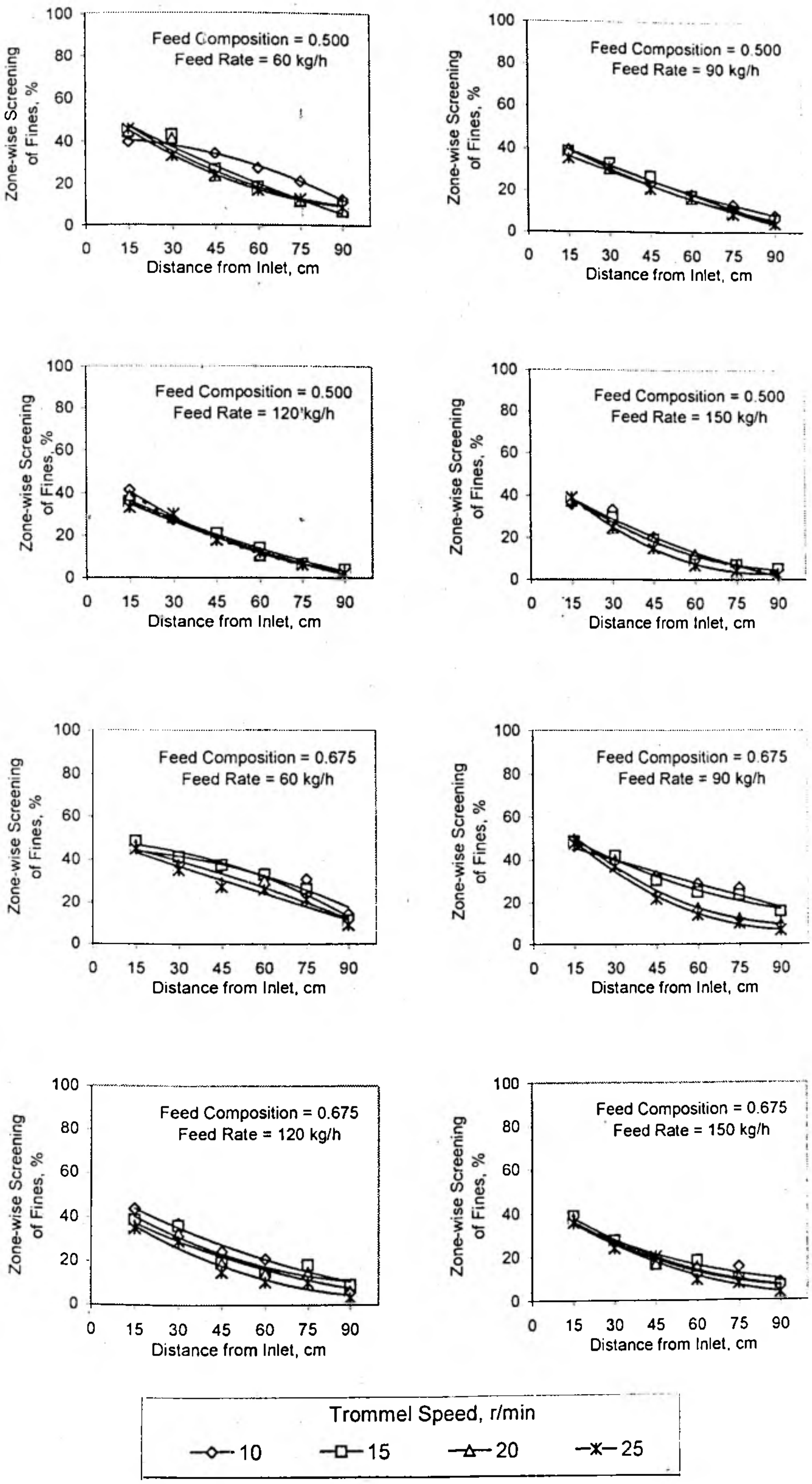


Fig. 5.15 Zone-wise screening percentage of fines at various trommel speeds, feed rates, and feed compositions (0.500 and 0.675) of the trommel of 4.75-mm apertures

In the last zone too, lower feed rates caused higher screening percentages. At enhanced rates of feed, more quantity of oversize particles reached the screen surface and enforced its deleterious effects. Therefore, higher feed rates were not at all advisable for trommels. Further, the variations in the trommel speed did not appreciably affect the screening percentages. Curves are, more or less, in one cluster. Still, the highest speed of 25 r/min generated lower screening percentages due to the increased peripheral velocities. This emphasised again of the need for maintaining lower trommel speeds for maximum particle passage. Data indicated that the speed, 10 r/min, was generally more advisable.

Further, the results demonstrate that a good quantity of undersize particles was still left to be separated from the overflow occurring from the last zone. It could be possible to separate them by either increasing the length of screen or subjecting the tailings to a second pass through the screen. Further investigation is necessary on this aspect. It is, hence, suggested for studies in future.

From the above, the following major conclusions are as follows:

1. In general, higher feed compositions and lower feed rates produced higher zone-wise screening percentage of fines.
2. The change in trommel speed, generally, did not exhibit pronounced effect on the zone-wise screening percentage of fines.
3. Zone-wise screening percentage, generally, decreased with the increase in the zone's distance from the inlet end of trommel.
4. As much as 50 per cent of the undersize material in the feedstock got separated in the first zone itself, especially at higher feed composition.
5. The zone-wise screening percentage of fines was, mainly, dependent on the quantity of undersize material on the screen.

5.6.3 Clogging index

Clogging index denotes the percentage of apertures clogged out of their total number on the screen. Results of the experiments and the analyses of data, for determining the clogging indices of the three trommels, are presented in Appendix-F (Tables F-4 through F-6 and F-8 through F-10). Results of the ANOVA carried out, based on the data in Tables F-8 through F-10, are presented in Table 5.13 and discussed.

Table 5.13 Analyses of variance for the effect of feed composition, feed rate, and trommel speed on clogging index of trommels

Source of Variation	df	SS	MSS	F
	Aperture Diameter = 4.00 mm			
Feed Composition (F_C)	3	0.101	0.034	35.29**
Feed Rate (F_T)	3	0.071	0.024	24.86**
Trommel Speed (N)	3	0.010	0.003	3.49*
F_C x F_T	9	0.076	0.008	8.78**
F_C x N	9	0.024	0.003	2.74**
F_T x N	9	0.017	0.002	1.94*
F_C x F_T x N	27	0.023	0.001	0.90^{NS}
Error	320	0.307	0.001	
Total	383	0.629		
	Aperture Diameter = 4.25 mm			
Feed Composition (F_C)	3	0.031	0.010	8.88**
Feed Rate (F_T)	3	0.043	0.014	12.44**
Trommel Speed (N)	3	0.006	0.002	1.65^{NS}
F_C x F_T	9	0.059	0.007	5.68**
F_C x N	9	0.022	0.002	2.15*
F_T x N	9	0.013	0.001	1.24^{NS}
F_C x F_T x N	27	0.065	0.002	2.08**
Error	320	0.370	0.001	
Total	383	0.609		
	Aperture Diameter = 4.75 mm			
Feed Composition (F_C)	3	0.026	0.009	7.09**
Feed Rate (F_T)	3	0.042	0.014	11.44**
Trommel Speed (N)	3	0.017	0.006	4.54**
F_C x F_T	9	0.016	0.002	1.42^{NS}
F_C x N	9	0.061	0.007	5.56**
F_T x N	9	0.013	0.001	1.16^{NS}
F_C x F_T x N	27	0.045	0.002	1.38^{NS}
Error	320	0.389	0.001	
Total	383	0.609		

** Significant at 1 per cent level

* Significant at 5 per cent level

NS Not significant

The highest value among the grand means of clogging indices of the three trommels was only 0.18 per cent, which was that of the trommel of smallest apertures. The maximum and minimum were 0.02 and 0.25 per cent respectively. It confirms that clogging was not a matter of any serious concern in the trommels studied. The data show also that the clogging was not cumulative in the trommels. This is contrary to the findings in respect of the oscillating flat tray screens (Fink, 1958; English, 1974; Feller *et al.*, 1986; Bosoi *et al.* 1990). Unlike the oscillation, the rotary motion of the trommel in the vertical plane is conducive for both the particle passage and the dislodging of trapped particles from the apertures. Also, the changes in clogging index, due to the changes in levels of these parameters relating to the trommel having apertures of 4.00 mm diameter, are depicted in Figures 5.16 through 5.18. Their effects on clogging are discussed more in detail below.

5.6.3.1 Effect of feed composition

The four levels of feed compositions used were 0.150, 0.325, 0.500 and 0.675. As seen in the ANOVA, the main effect of this parameter is highly significant. It is known that oversize particles cause clogging, particularly the near-mesh particles. Since, feed composition decided the quantity of these particles in the feedstock; its effect was bound to be significant. Regression analyses show that, generally, a second-degree polynomial equation of the following form best represented the relationship between clogging index (C_i) and feed composition (F_C) with a high correlation coefficient for all the trommels.

$$C_i = a_0 + a_1 F_C + a_2 F_C^2 \qquad \text{...(5.20)}$$

Figure 5.16 illustrates the changes in clogging index with respect to feed composition at different levels of feed rate and trommel speed for the trommel of 4.25 mm apertures. The general trend with this trommel was for the clogging index to vary in either direction. indicating that the particles clogging the apertures were getting unseated frequently. Almost a similar trend was observed in the case of the trommel of 4.75 mm apertures. However, it was the reverse for the trommel having the smallest apertures. The berries lodged in larger apertures were, obviously, bigger in size, and consequently heavier. This assisted them in getting released from the apertures more easily when the apertures, together with the berries seated in them, rose to the top of the trommel during its rotation.

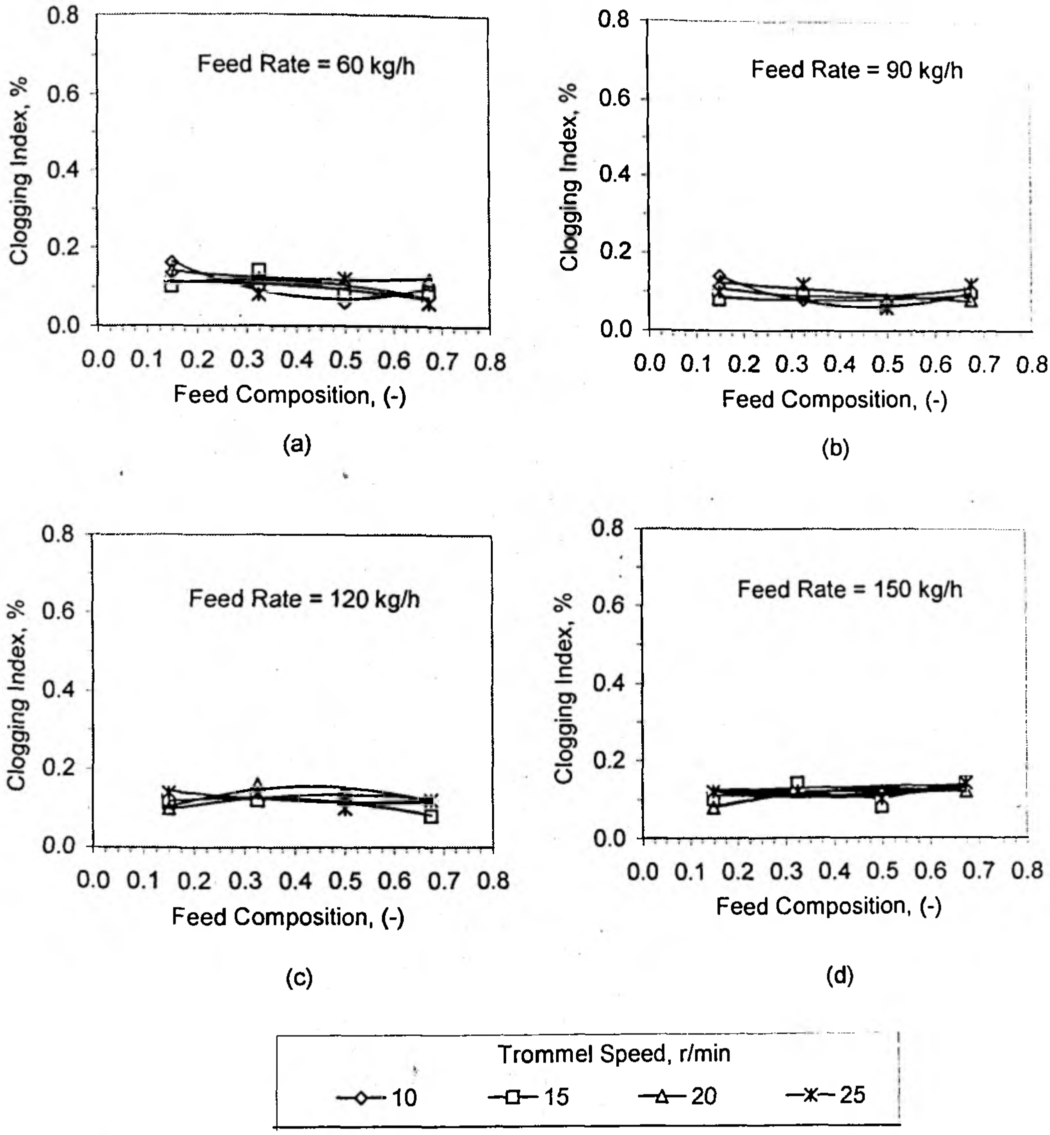


Fig. 5.16 Response of clogging index to changes in feed composition at different trommel speeds and feed rates of the trommel of 4.25-mm aperture diameter

This reduced clogging. However, in many cases with the trommel of smallest apertures, there was a reduction in the clogging indices at the levels of 0.325 and 0.500, before rising to higher indices at the level of 0.675. This occurred mostly for the feed rates up to 120 kg/h. At lower feed compositions, the quantity of oversize berries was lesser, and at lower feed rates, the bed thickness was lesser. So, the number of near-mesh particles pressed into apertures was fewer. Correspondingly, there was a reduction in clogging index. Conversely, it was more at higher feed compositions and feed rates. The adverse effect due to this was observable in respect of all the trommels; *i.e.*, higher clogging index. The variation in clogging index due to different levels of trommel speed at various feed compositions and feed rates was not large for the three trommels. All the curves were more or less close to each other. Due to slow rotation of the trommels, the centrifugal forces were not considerable enough to cause large-scale clogging. Therefore, within the levels of feed composition studied, the trommels could be operated at any of these speeds, particularly 20 r/min, without causing large-scale clogging. Further, a comparison was made with the results presented in Section 5.4.2.1 on the oscillating flat screen. Unlike the trommels, the effect of feed composition on clogging index of the oscillating flat screen was to invariably increase it with the increase in feed composition. Besides, the clogging indices were comparatively higher for the oscillating flat screen at the two feed compositions considered, in spite of the small difference in feed composition at one of the levels; 0.325 for the trommel and 0.330 for the other.

5.6.3.2 Effect of feed rate

The feed rates studied were 60, 90, 120 and 150 kg/h. The high significance of the main effect of this parameter was noticeable from the ANOVA for all the trommels (Table 5.13). Since the total number of oversize particles reaching the screen surface at any instant was varied by the feed rate, it changed the number of apertures clogged. The relationship between the feed rate (F_T) and the clogging index (C_i) was established through regression analyses. In general, it was best represented by a second-degree polynomial equation of the following form with a high correlation coefficient.

$$C_i = a_0 + a_1 F_T + a_2 F_T^{\,2} \qquad \ldots(5.21)$$

Besides, the relationship in respect of the trommel of 4.25 mm apertures is exhibited in Fig. 5.17. The general trend was for the clogging index to rise with the increase in feed rate, though not at an appreciable rate. Reasons were the same as those explained above. For the trommel of aperture diameter, 4.00 mm, also the overall trend was the same. But, the trend was reverse for the curve representing the feed composition of 0.150. After a rise through the lower levels of feed rate, it decreased at higher feed rates. This is a strange behaviour. No reason could be detected for this anomalous behaviour. Perhaps, it could have happened due to some randomness.

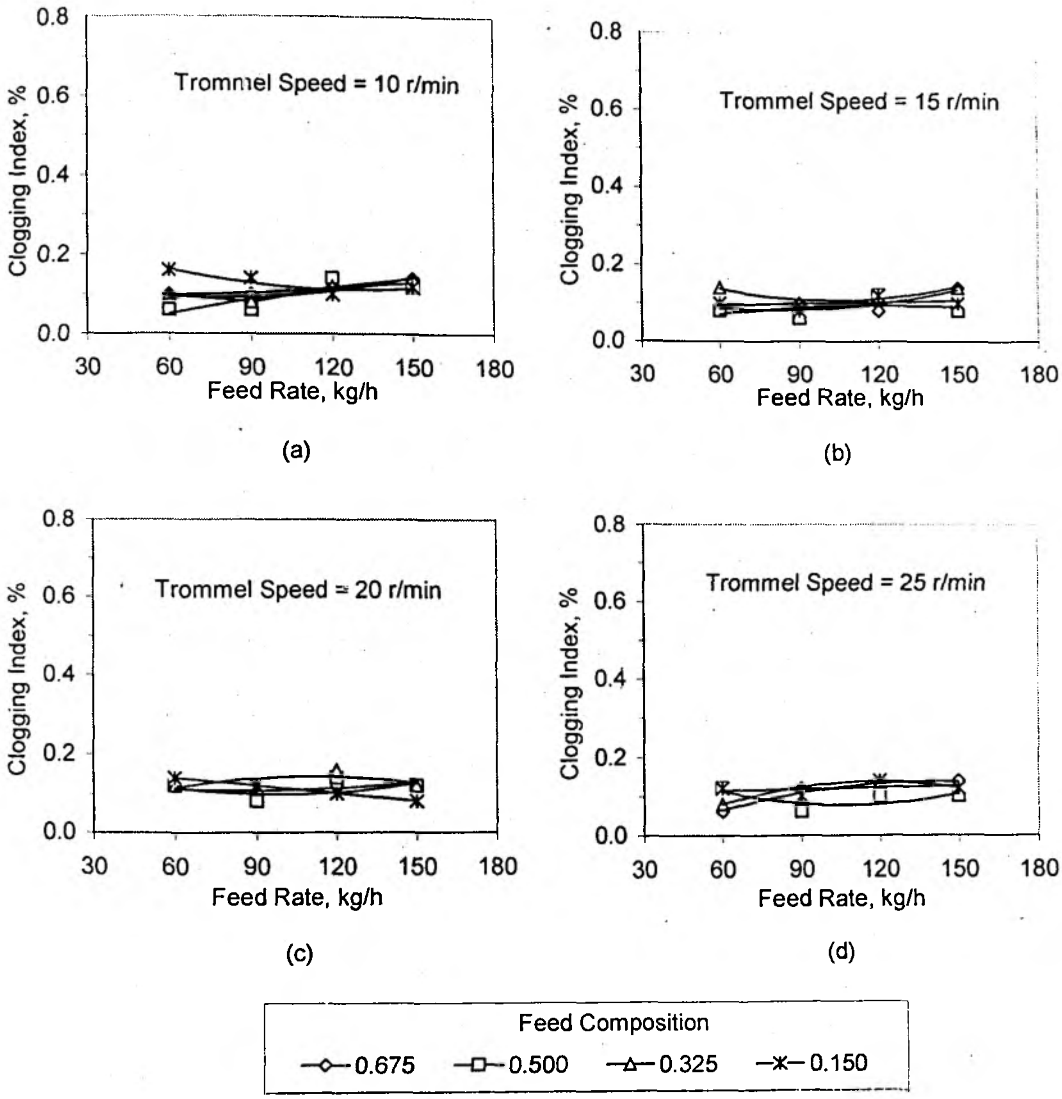


Fig. 5.17 Response of clogging index to changes in feed rates at different feed compositions and trommel speeds of the trommel of 4.25-mm aperture diameter

It was also seen that, at all the levels of feed rates, the higher values of clogging index were, in general, given by the feed composition which supplied the maximum quantity of oversize particles. But, the curves for 0.325 and 0.500 showed much lower values than those of the feed composition, 0.150. This compelled to infer that the role of some other factor was more dominant than those considered in the present study. This appeared to be that of the surface characteristics of black pepper. There was a network of wrinkles on its surface. As a result, there were more chances for the berries for getting interlocked with

the edge of the aperture. It was observed during the experiments that the interlocking was not very firm in many cases; *i.e.*, it was loosely interlocked. Therefore, many of them tumbled down at one time or the other depending upon their orientation in the aperture, size of the wrinkles and other irregular projections on the surface, attrition of the interlocking projections, vibration of the screen element at the location of aperture, and weight of the particles. This might have been taking place randomly. It was felt that these aspects needed further studies. It is being proposed for future studies. It was seen that the rate of change of clogging index was smaller at higher trommel speeds. This could be due to the increased vibrations induced on the screen element due to the repeated cascading of particles from the flights at shorter intervals.
The increase in clogging index of the trommels of diameters, 4.25 and 4.75 mm, was not as high as that of the trommel of 4.00-mm apertures. It might be due to the favourable effect produced by the heavier particles, in falling from the aperture during rotation. The randomness appeared to be applicable more to these trommels. The effect due to the variations in feed composition was also seen to be highly fluctuating. But for the changes in feed rates, the increase in speed, however, did not appreciably change the clogging index. Again, this might be due to the shortened intervals of particle cascading.

Based on the above, it was seen that it was advantageous to maintain lower feed rates in the trommels, though higher feed rates did not pose serious problems of clogging. The necessity for maintaining lower feed rates was applicable also to the oscillating screens. The result presented in Section 5.4.2.2, on the oscillating flat screen, was in support of this. Unlike the trommels, the increase of feed rate considerably raised the clogging index in the oscillating screen. Rose (1977) reported that the feed rate affected not only the load on the screen but also the screen motion. The screen oscillation and the consequent vibration of screen element change according to the feed rates. At higher feed rates, these are conducive for clogging. Feller *et al.* (1986) suggested that the material be fed in a thin layer to overcome this problem.

5.6.3.3 Effect of trommel speed

The experiments were conducted at the trommel speeds, 10, 15, 20, and 25 r/min. The result of ANOVA presented in Table 5.13 shows that the main effect of trommel speed was not uniform for the three trommels. Similarly, the interactions too were varying in significance. It revealed also that the trommel speed, within the range studied, exerted only the least effect compared to the feed rate and the feed composition. This might be because, within the levels selected, the speed was not causing a direct influence in varying the clogging index. As observed during the experiments, a particle was seated in an aperture, mainly, in three different ways: (i) *loosely seated*, (ii) *loosely seated but interlocked with the edge of aperture*, and (iii) *firmly wedged in the aperture*. As the screen element rotated in a vertical plane, the particle under the first condition became unstable at angles higher than the angle of rolling friction and rolled off the aperture. So, this aperture became available for screening as it reached the bottom at the end of a rotation. This means, there was no permanent clogging. As long as the speed was below the critical speed, this process took place irrespective of the level of speed. So, the change in speed was irrelevant. The particle under the third condition was also not influenced by the change in speed. It remained firmly wedged whatever be the speed. So, a change in speed did not vary the clogging index. At the same time, the particles under the second condition fell off the aperture at random during the rotation of trommel. Their behaviour appeared to be guided more by the factors cited in Section 5.6.3.2, like surface characteristics, vibration, attrition, etc. This produced random variations in clogging index. One of the factors that was seen to dislodge a particle loosely interlocked in the aperture was the vibration of screen element. Vibration forces that particle to keep changing its orientation repeatedly. At one instant, it places the second dimension of the particle across the aperture so that it can gain passage through the aperture. Similarly, it also effects shifting of the particle's projections, which are responsible for temporary interlocking, away from the plane of the aperture. This enables the particle to drop off the aperture at angles above that of the rolling friction. Besides, vibrations also bring about attrition of the projections on the surface of particle. All these lead to changes in clogging index. But, all these occur at random. One among the forces seen to be inducing vibration in the screen element was the impact force exerted on it by the particles, at the end of their cascading from the flights. Their strike-velocity was dependent also on the trommel speed. Hence, speed was responsible to some extent for varying the clogging index. But, as it was taking place randomly, its main effect and interaction effects were non-uniform.

The relationship between clogging index (C_i) and trommel speed (N), established through regression analyses, was best represented by a second-degree polynomial equation of the following form with a high correlation coefficient.

$$C_i = a_0 + a_1 N + a_2 N^2 \qquad \ldots(5.22)$$

The response of clogging index to the changes in trommel speed is illustrated in Fig.5.18.

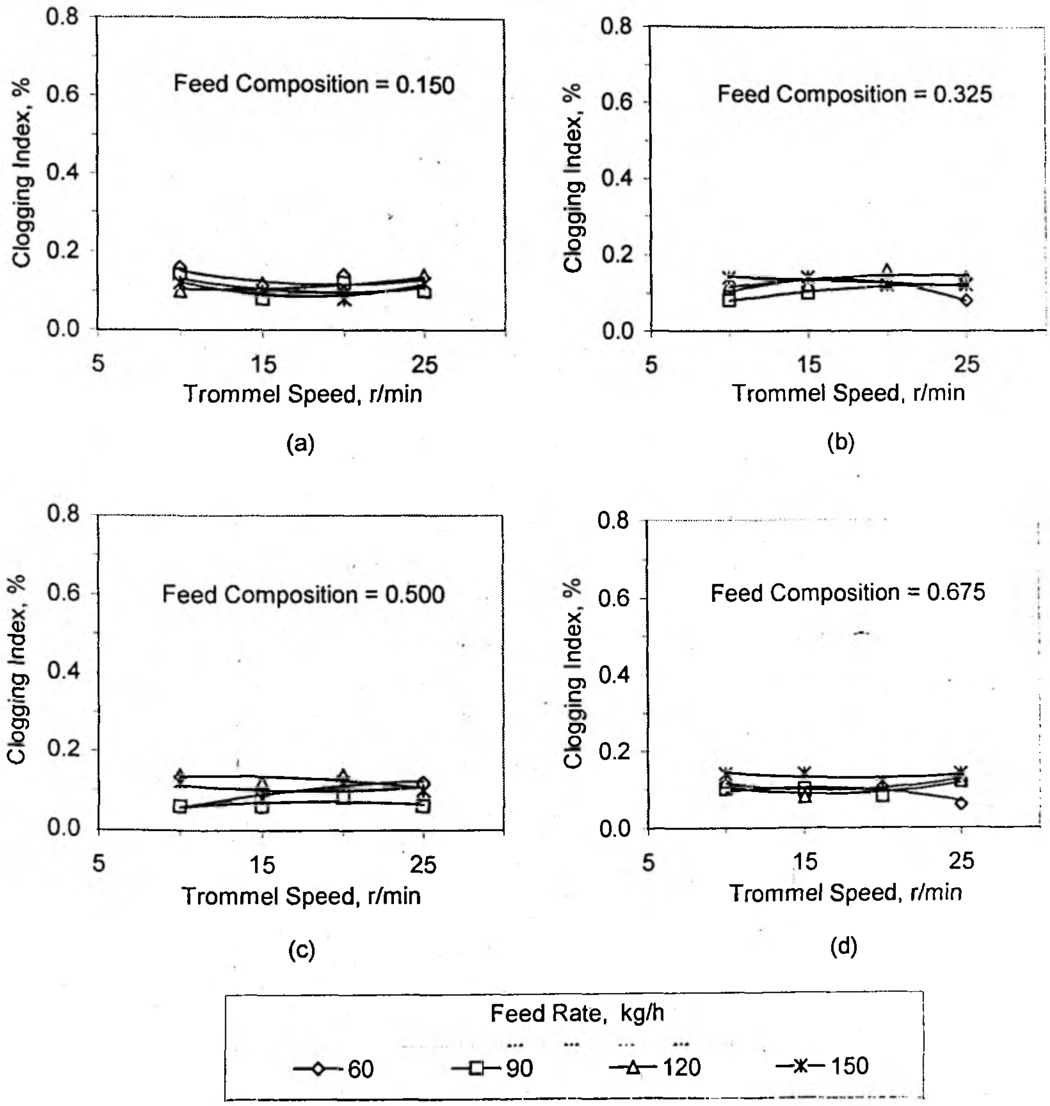


Fig. 5.18 Response of clogging index to changes in trommel speeds at different feed rates and feed compositions of the trommel of 4.25-mm aperture diameter

It indicates that the trend was not the same for the three trommels. This appeared to be owing to the randomness in the process. The general trend with the trommel having 4.00-mm aperture size was to maintain more or less a uniform clogging index with the increase in speed. However, the speed best suitable for producing the lowest clogging index was 25 r/min at 60 kg/h with a feed composition of 0.325. The one for a feed composition of 0.150 was 15 r/min at 60 kg/h. The trend of the trommel of 4.25-mm aperture was also to maintain a uniform clogging index. The ANOVA also shows that the effect of speed was non-significant in its case. Comparatively, the speed of 20 r/min at 150 kg/h produced the lowest clogging index for the feed composition 0.150. For the trommel of 4.75-mm aperture, the main effect of speed was significant at 1 per cent level. Except at the lowest feed composition, speed produced a steadily decreasing trend in clogging index. This might be due to the intense vibrations induced at enhanced strike-velocities of the particles. Besides, the particle size was also larger. The lowest clogging index was at 25 r/min for a feed rate of 60 kg/h and feed composition, 0.675. The reason for the reverse trend at the feed composition of 0.150, however, could not be traced. The speed suitable for producing the lowest clogging index for the feed composition of 0.150 was, however, the lowest one, 10 r/min, at a feed rate of 60 kg/h.

However, the effect of screen speed on clogging index, as observed in the present study, was different from that of the oscillating screen; of course, one relates to rotation and the other to oscillation. Clogging invariably increased with the reduction in oscillation frequency. Findings of other researchers are also in support of this (Fink, 1958; English, 1974; Feller *et al.*, 1986; Bosoi *et al.*, 1990). Further, this was observable also in the results presented in Section 5.4.2.3 on the oscillating screen.

5.6.3.4 Interaction effect

The ANOVA shows that, unlike for the screening inaccuracy, the 2-variable and 3-variable interactions had different levels of significance for the three trommels (Table 5.13). The treatment means, required for showing the effects of significant interactions, are furnished in Tables 5.14 and 5.15 and Appendix-H (Tables H-5 and H-6) for the three trommels. The level of significance pertaining to the difference between any two treatments is observable from these means. The values of statistical least significant difference (LSD), for the levels of significance at 1 and 5 per cent, are also furnished along with the tables.

Table 5.14 Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, and trommel speed, on clogging index of the trommel of 4.00-mm apertures

Feed Composition (F_C) (-)	Mean Clogging Index, %								
	Feed Rate (F_T), kg/h				Trommel Speed (N), r/min				Mean
	60	90	120	150	10	15	20	25	
0.150	0.091	0.122	0.124	0.104	0.107	0.114	0.107	0.113	0.110
0.325	0.071	0.082	0.107	0.140	0.097	0.092	0.110	0.101	0.100
0.500	0.101	0.087	0.078	0.139	0.115	0.094	0.088	0.107	0.101
0.675	0.132	0.133	0.139	0.158	0.152	0.142	0.117	0.150	0.140
Feed Rate (F_T), kg/h									
60	-	-	-	-	0.111	0.097	0.081	0.106	-
90	-	-	-	-	0.104	0.103	0.104	0.112	-
120	-	-	-	-	0.115	0.101	0.107	0.126	-
150	-	-	-	-	0.142	0.141	0.131	0.126	-
Mean	0.099	0.106	0.112	0.135	0.118	0.111	0.106	0.118	-

LSD *for*	Significance Level 0.01	0.05
F_C	0.015	0.008
F_T	0.015	0.008
N	0.015	0.008
$F_C \times F_T$	0.018	0.012
$F_C \times N$	0.018	0.012
$F_T \times N$	0.018	0.012

Table 5.15 Mean values showing 3-variable interaction effect, among feed composition, feed rate, and trommel speed, on clogging index of the trommel of 4.25-mm apertures

Feed Rate (F_T) kg/h	Mean Clogging Index, % — Feed Composition (F_C), (-)															
	0.675				0.500				0.325				0.150			
	Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min			
	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	0.097	0.087	0.110	0.067	0.063	0.073	0.110	0.113	0.107	0.140	0.110	0.087	0.168	0.100	0.137	0.127
90	0.097	0.107	0.077	0.120	0.060	0.060	0.070	0.057	0.070	0.100	0.110	0.117	0.137	0.077	0.120	0.097
120	0.117	0.080	0.120	0.113	0.130	0.117	0.142	0.103	0.113	0.120	0.155	0.137	0.103	0.117	0.100	0.133
150	0.140	0.142	0.110	0.145	0.110	0.080	0.113	0.103	0.142	0.130	0.123	0.120	0.113	0.100	0.077	0.120

LSD *for*	Significance Level 0.01	0.05
$F_C \times F_T \times N$	0.034	0.024

Two-variable interaction: The interaction effect due to feed composition and feed rate was significant for only the trommels of 4.00- and 4.25-mm apertures. It was seen that the changes in feed composition at various levels of feed rate were producing non-significant variations in the clogging index in a number of cases. The same trend was seen for the changes in feed rate at different levels of feed composition. The increase in feed composition from the lowest level initially lowered clogging index at the feed rates 60, 90, and 120 kg/h for the trommel of 4.00-mm apertures. The clogging index, however, peaked at the highest feed composition. At the highest level of feed rate, the change in fed composition produced a zigzag trend. The trend with the trommel of 4.25-mm was puzzling. Each feed rate produced a different kind of trend for the change in feed composition. Similarly, the pattern of variation in clogging index, for the changes in feed rate, was also different at the various levels of feed composition for the two trommels. All these indicated that clogging was not cumulative in the hexagonal flighted-trommels.

The interaction effect due to feed composition and trommel speed was significant for all the trommels; though at different levels. It was observed that the changes in feed composition at various levels of trommel speed were leading to non-significant variations in the clogging index in only few cases. For the trommel of 4.75-mm apertures, the entire variations were highly significant. The interaction effect of these parameters were also producing non-uniform pattern of variation in clogging index for the changes in feed composition, and trommel speed. This also emphasised that clogging was not cumulative. The interaction effect due to feed rate and trommel speed was significant only for the trommel of 4.00-mm apertures. It was seen that the changes in feed rate at various levels of trommel speed were resulting in non-significant variations in the clogging index in a number of cases for this trommel. The changes in trommel speed at various levels of feed rate also showed a similar trend. The changes in clogging index brought about by the increase in feed rate at various levels of trommel speed were differing in their trend. However, the overall trend due to interaction was to increase the clogging index. Similarly, the increase in trommel speed at the various levels of feed rate was also changing the clogging index generally in the same manner. But, lower clogging indices were produced for the changes between intermediate levels. However, these variations in the clogging index were either non-significant or lower in level of significance. Hence, the interaction due to feed rate and trommel speed also did not cause serious clogging.

Three-variable interaction: The ANOVA indicates that the only 3-variable interaction having significance was that of the trommel of 4.25-mm apertures (Table 5.13). The treatment means presented in Table 5.15 were used in analysing the 3-variable interaction of this trommel. A comparison with the LSD values show that the variations in treatment means were non-significant in a large number of cases. The randomness in the effect of interaction on clogging index, as observed in the 2-variable interactions, was discernible in this case too.

Therefore, it could be seen that, in size classifying black pepper with the hexagonal flighted-trommels, neither the 2-variable nor the 3-variable interactions produced large-scale clogging. It was also inferred that the clogging was not cumulative.

Based on the results and the discussion presented in Section 5.6.3 on clogging index of hexagonal flighted-trommels, the major conclusions drawn are as follows.

1. In general, higher feed compositions produced higher clogging indices in the trommel of small apertures, and lower feed compositions produced higher clogging indices in the trommel of larger apertures.
2. Higher feed rates led to, generally, higher clogging indices in trommels.
3. Trommel speed, in general, did not vary the clogging index considerably in the trommels, though in some cases it reduced clogging at higher speeds.
4. The highest value among the grand means of clogging indices of the three trommels was only 0.18 per cent, which was that of the trommel of smallest apertures. The maximum and minimum were 0.02 and 0.25 per cent respectively.
5. Rotary motion of the trommel facilitated not only particle passage through the apertures but also the clearing of clogged apertures.
6. Clogging was not cumulative with respect to time.

5.6.4 Power requirement

The power required by the three hexagonal flighted-trommels, in size classifying black pepper, was determined as described in Sections 4.2.3.7, 4.3.5, and 4.3.6. The calibration curves, separately plotted for each speed using the regression technique, gave the output power for any input power to the power supply system (Fig. 5.19). These were prepared based on the results of prony brake dynamometer test, conducted at various loads and the trommel-shaft speeds of 10, 15, 20, and 25 r/min. The regression analyses yielded the following four equations in which the input power (P_i) and the output power (P_o) correlated well with a R^2 of 0.99 for all the speeds.

At 10 r/min, $P_o = 0.0236\ P_i - 2.7111$ ...(5.23)

15 r/min, $P_o = 0.0224\ P_i - 2.8311$ ...(5.24)

20 r/min, $P_o = 0.0199\ P_i - 2.6798$ ...(5.25)

25 r/min, $P_o = 0.0181\ P_i - 2.5358$ ...(5.26)

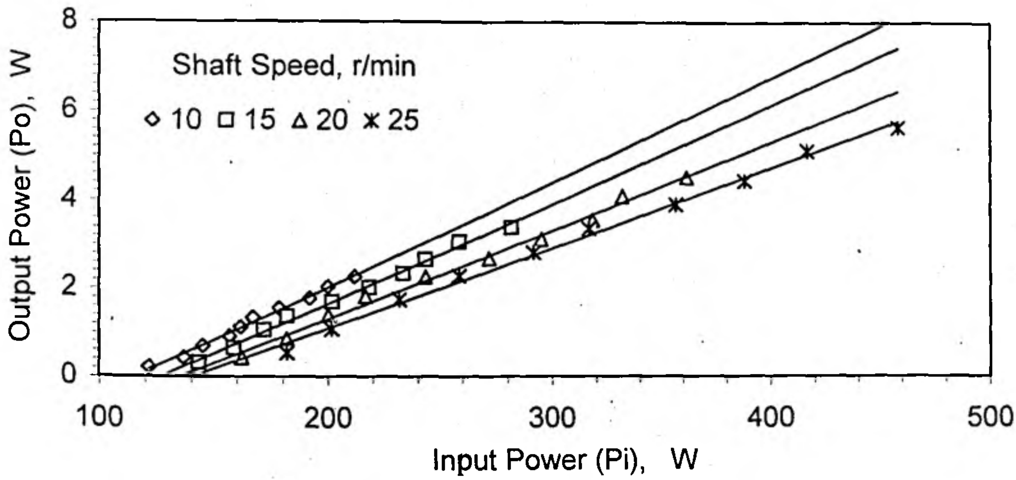


Fig. 5.19 Relationship between input and output of the power supply system

The power requirements of the trommels, at different feed rates and trommel speeds, were determined by substituting in the respective equations the observed input power to the experimental set-up. De (1985) used a method similar to these for determining the power requirement of flow-aiders in a fertilizer distribution system. Since, feed composition was considered to be not affecting the power requirement, its various levels were not taken into account. However, the measurements were made at the highest of the four feed compositions. According to the ANOVA given in Table 5.16, based on the power requirements of the trommels, main effects of both the feed rate and the trommel speed were highly significant for all the trommels. The result hints that the main effect of feed rate was more dominant. This was mainly due to the significant variations in the quantities of materials required to be conveyed at the various levels of feed rate. At the same time, the different levels of trommel speeds were comparatively not greater enough to produce substantial changes in the power requirement. Mean values of the power requirement at different levels of feed rate and trommel speed of the three trommels are given in Table 5.17.

Table 5.16 ANOVA for the effect of feed rate and trommel speed on power requirement of the three trommels

Source of Variation	df	SS	MSS	F	SS	MSS	F	SS	MSS	F
		Aperture Diameter, mm								
		4.00			4.25			4.75		
Feed Rate (F_T)	3	7.17	2.39	131.4^{**}	8.63	2.88	214.8^{**}	9.20	3.07	279.4^{**}
Trommel Speed (N)	3	2.10	0.70	38.4^{**}	1.35	0.45	33.7^{**}	0.88	0.29	26.8^{**}
F_T x N	9	0.07	0.01	0.4^{NS}	0.13	0.01	1.07^{NS}	0.09	0.01	0.86^{NS}
Error	80	1.46	0.02		1.07	0.01		0.88	0.01	
Total	95	10.79			11.19			11.05		

** Significant at 1 per cent level
NS Non-significant

Table 5.17 Mean values showing main effect of feed rate and trommel speed on power requirement of the three trommels

Aperture Diameter of Trommel, mm	Mean Power Requirement, W							
	Feed Rate (F_T), kg/h				Trommel Speed (N), r/min			
	60	90	120	150	10	15	20	25
4.00	0.86	1.00	1.24	1.58	0.97	1.12	1.24	1.37
4.25	1.02	1.12	1.29	1.80	1.14	1.27	1.34	1.47
4.75	1.03	1.15	1.33	1.84	1.20	1.32	1.37	1.47

LSD *for*	Significance Level 0.01	0.05
Aperture Diameter of Trommel = 4.00 mm		
F_T	0.12	0.06
N	0.12	0.06
Aperture Diameter of Trommel = 4.25 mm		
F_T	0.11	0.06
N	0.11	0.06
Aperture Diameter of Trommel = 4.75 mm		
F_T	0.10	0.05
N	0.10	0.05

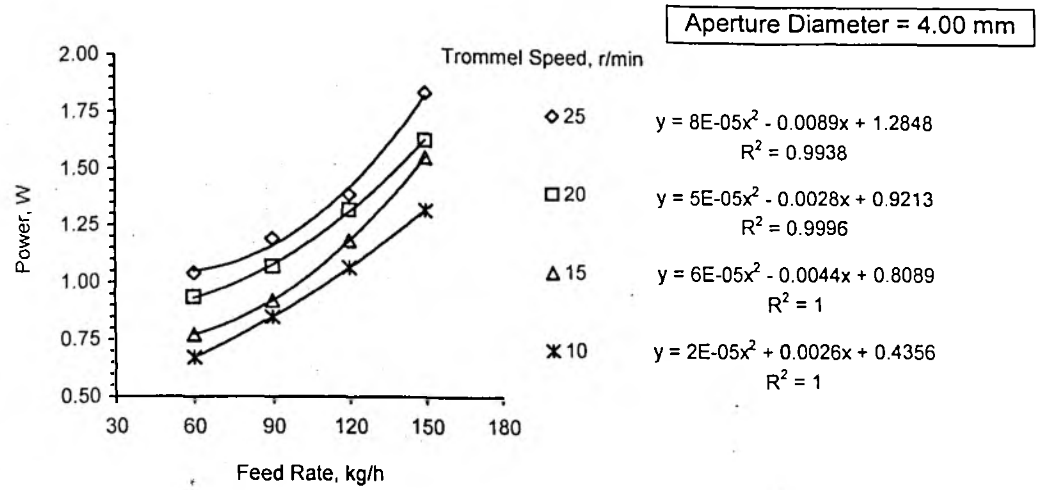
The values of statistical least significant difference (LSD) are provided along with the table. It is noted that all the observed variations in power requirement, due to changes in the levels of these two parameters, were significant at 1 per cent level for the trommel of 4.00-mm apertures. However, for the trommel of 4.25-mm apertures, the variations due to the change in level from 60 to 90 kg/h for the feed rate and that from 15 to 20 r/min for the speed, though significant, were only at 5 per cent level. Similarly, the variation for the change from 15 to 20 r/min of the trommel of 4.75-mm aperture too was significant at only 5 per cent level. Rest of the variations relating to these two trommels was highly significant. Reasons for the lower level of significance could not be traced. The ANOVA shows also that the interaction effects were not at all significant for the three trommels.

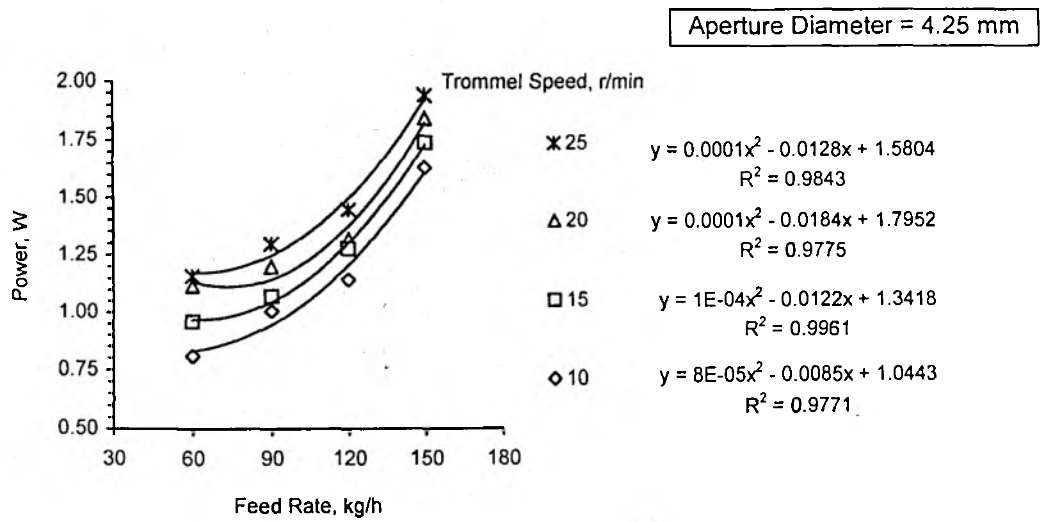
5.6.4.1 Effect of feed rate

The power requirement of al the three trommels over a range of feed rates at different trommel speeds, are shown in Fig. 5.20. The regression equations representing the relationship between the feed rate and the power requirement are also presented in the same. It could be seen that second-degree polynomial equations best represented the relationships with high R^2-values. According to the pattern seen in the figures, the power requirement increased with the increase in feed rate. This was quite natural too. The maximum power requirement occurred at the highest feed rate and the minimum at the lowest for all the three trommels. The curves also showed that the power requirement, generally, increased rapidly after the second feed rate of 90 kg/h. It indicated of the disadvantage in maintaining higher feed rates. Even for obtaining lower screening inaccuracies, it was desirable that the trommels be operated at feed rates, 90 kg/h or below. Further, the power requirement showed higher values for the trommels having larger aperture size. This could be due to the greater mass of the oversize material remaining on a screen having larger aperture size.

5.6.4.2 Effect of trommel speed

Regression equations representing the relationship between trommel speed and power requirement were developed (Fig. 5.21). The second-degree polynomial equations best representing the relationships, had R^2-values over 0.92.





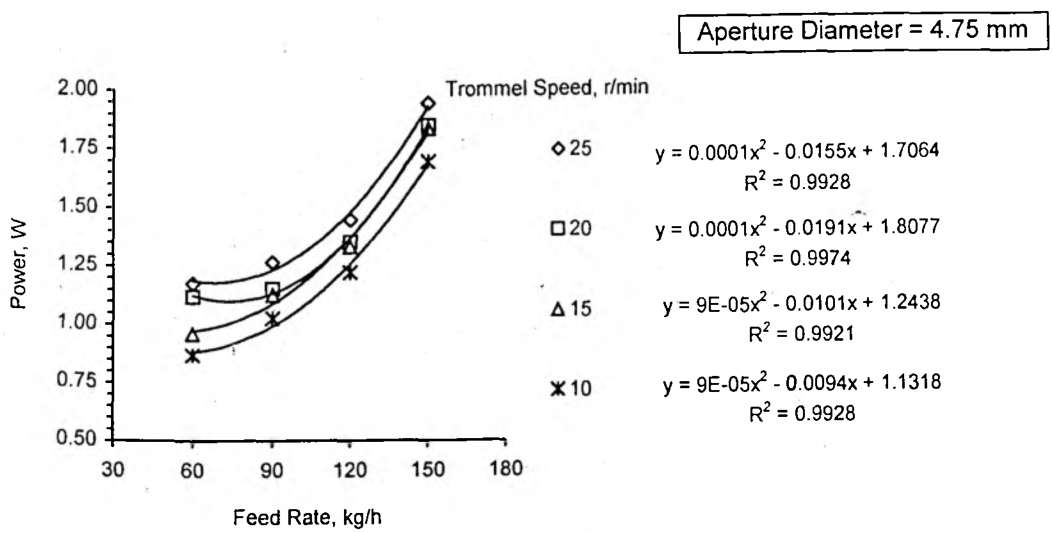


Fig. 5.20 Power requirement versus feed rate at various trommel speeds for the three trommels

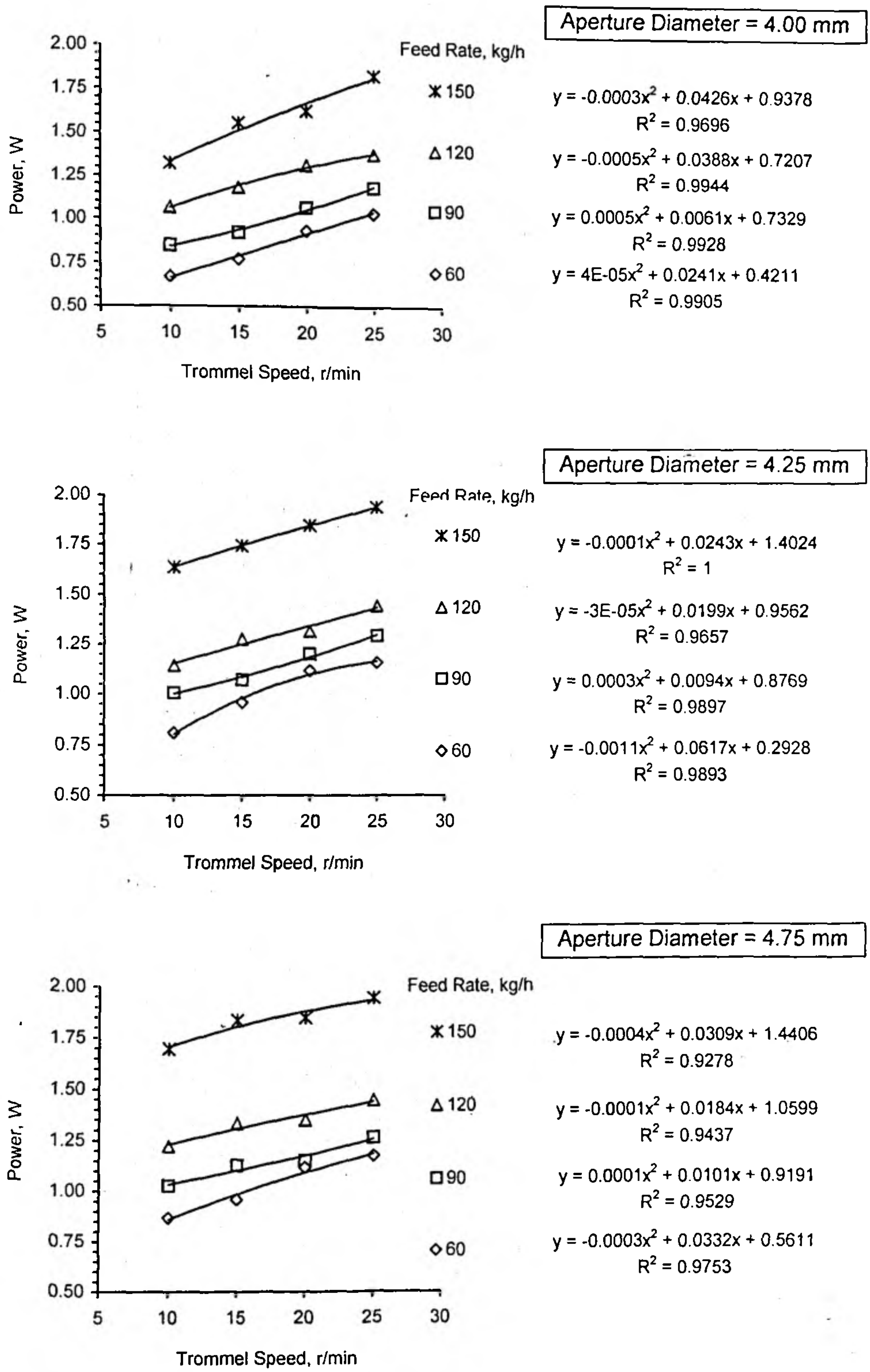


Fig. 5.21 Power requirement versus trommel speed at various feed rates for the three trommels

It could be seen that the power requirement increased with the rise in speed of rotation of the trommel. This is a standard pattern. Hence, the maximum power requirement was invariably at the highest speed of 25 r/min for all the trommels. Similarly, the minimum was at the lowest of the speeds. The maximum power requirement observed was 1.9 W. It was for the trommel having the largest apertures. Besides, it required only 0.7-1.1 W when operating to produce screening inaccuracies below 5 per cent. Reason for the same is already stated above. In the study by De (1985), the power requirement of the flow-aider rotated at 25 r/min, to stir 5.68 kg of dry fertilizer (Urea) in a hopper, was 5.8 W. According to him, the frictional resistance offered by the fertilizer caused higher power requirement. The trommel did not encounter such a resistance from the material it handled. In the trommel, it was only the transport or conveyance of loose granular material. Hence, the power requirement of trommel was bound to be lesser compared to the flow-aider. However, the higher power input to the whole power supply system, as observed in this study, was due to the needs of the step-down transformer, the speed controller, and the speed reduction gearbox of ratio 26:1.

Based on the above, the major conclusions drawn were as given below.

1. Increase in the feed rate and the trommel speeds increased the power requirement of the trommels.
2. The maximum power requirement of 1.9 W occurred at the highest feed rate of 150 kg/h and the highest speed of 25 r/min. Besides, it required only 0.7-1.1 W when operating to produce screening inaccuracies below 5 per cent. Therefore, the power requirement of the trommel was very low.

5.6.5 Cost of size classifying

The cost of size classifying black pepper in the hexagonal flighted-trommel was determined as shown in Appendix–I. It gave the unit cost of sizing at the screening inaccuracy tolerated by the Agmark Grade Specifications. The unit cost of sieving was only Rs 0.40 per kilogram at the feed rate of 90 kg/h; and that too with just one trommel. Therefore, there is scope for reducing this further by having a battery of many trommels. This would help in enhancing the total capacity of the respective processing plant and in making better use of the motor capacity.

At the same time, the unit cost of sieving was Rs 1.38 per kilogram for a manually-operated flat screen when achieving the said level of screening inaccuracy. A comparison with the oscillating flat screen was not attempted since this screen did not give the desired screening inaccuracy. Based on the above, it could be seen that hexagonal flighted-trommel was beneficial not only for obtaining the desired screening inaccuracy but also for making the sizing process more economical compared to the manual sieving.

5.7 Prediction of Screening Inaccuracy of a Hexagonal Flighted-Trommel using Empirical Models

Multiple regression analyses were conducted separately for each trommel utilizing the data presented in Appendix-F (Tables F-1 through F-6) to find out the relationship the trommel speed, the feed rate, and the feed composition had with the screening inaccuracy. As indicated by the high values of coefficient of determination (R^2), an empirical model of the following form well represented the relationships in respect of all trommels.

$$S_i = a_0 + a_1 F_C + a_2 F_T + a_3 N \qquad \text{...(5.27)}$$

where S_i = screening inaccuracy, %;
a_0, a_1, a_2, and a_3 = constants.

The multiple regression models developed for the three trommels are given below.

1. For the trommel of 4.00-mm aperture diameter

$$S_i = 30.3 - 61.257F_C + 0.1005F_T + 0.409N \qquad \text{...(5.28)}$$
$$(R^2 = 0.97; \quad F = 698.82^{**})$$

2. For the trommel of 4.25-mm aperture diameter

$$S_i = 29.2 - 54.682F_C + 0.0923F_T + 0.344N \qquad \text{...(5.29)}$$
$$(R^2 = 0.98; \quad F = 879.92^{**})$$

3. For the trommel of 4.75-mm aperture diameter

$$S_i = 30.6 - 56.632F_C + 0.1075F_T + 0.279N \qquad \text{...(5.30)}$$
$$(R^2 = 0.98; \quad F = 1234.16^{**})$$

The F values indicate that the relationships were significant at 1 per cent level. The high values of coefficient of determination (R^2) show that these models could predict screening inaccuracy with reasonable accuracy. A comparison between the values of screening inaccuracy predicted and observed has also been made, by determining the percentage deviation between the two, as presented in Appendix-E (Table E-1). The observed values used in this comparison were those obtained from a separate set of experiments using the three trommels. Its data were those in Appendix-G (Table G-1).

The data in Table E-1 indicates that, though the two values were, in general, close to each other for all the trommels, the range was quite large. The grand means of their percentage deviation; considering all the three trommels; varied from –60.6 to 121.9 per cent. Barring these two extreme values, the next extreme values were -57.3 and 74.4 per cent. The larger values were occurring, particularly, for the lower feed rates at the highest feed composition. It was at these factor combinations that the lower observed values were occurring. So, a small deviation reflected heavily on the percentage deviation. Extremely higher values were, however, only fewer in numbers. Hence, the models can be used in predicting the screening inaccuracy with reasonable accuracy. Besides, Fig. 5.22 shows the correlation between the observed and the predicted values of screening inaccuracy of the three trommels. The correlation coefficient (R') over 0.9 was common to all the three trommels. It suggests that the prediction of screening inaccuracy, using the proposed empirical models, was reasonably accurate. The relationship in each of the three cases was given by a straight line close to 45^0. It confirmed the validity of empirical models.

5.8 Comparison of the Models Used for Predicting Screening Inaccuracy of a Hexagonal Flighted-Trommel

A comparison between the values of screening inaccuracy observed and those predicted by the semi-empirical model (Eqn 3.22) and the multiple regression models (Eqns. 5.28 through 5.30) of the three trommels was made using Figs. 5.8 and 5.22, and the data in Appendix-E (Table E-1). The figures show the correlation between the observed and the predicted values, whereas the table gives the percentage deviation between the two. These indicate that the empirical model predicted the screening inaccuracy better; though the two extreme values were quite large (–60.6 to 121.9 per cent) for the three trommels. At the same time, the extreme values (–34.7 to 44.5 per cent) given by the semi-empirical model were comparatively closer to the observed values. Further, the figures of both the models show that both the models, by and large, underestimated the screening inaccuracies. Reason for the same could not be traced.

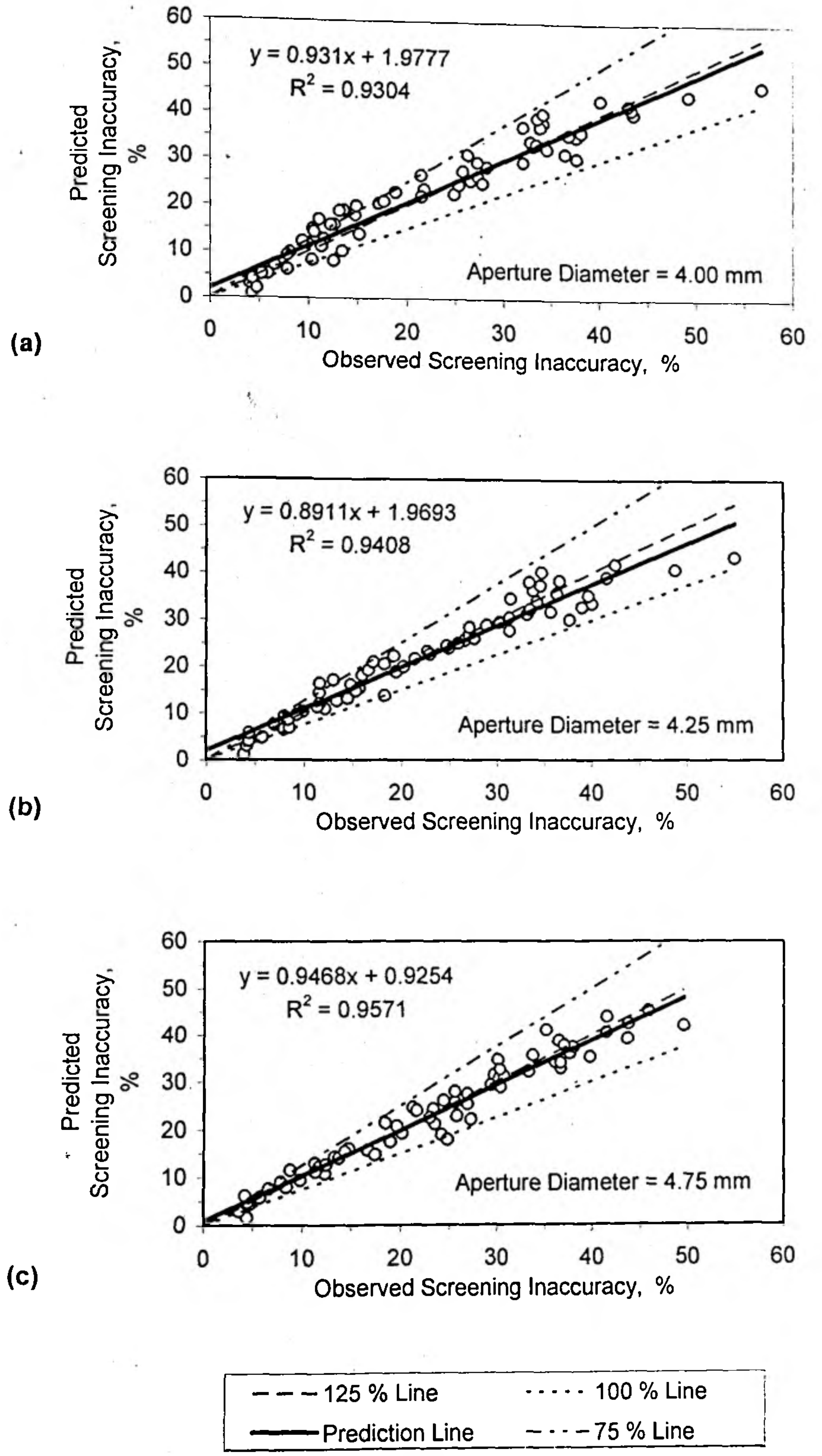


Fig. 5.22 Comparison of values of screening inaccuracy predicted by the empirical model with those observed

Similarly, a comparison of the prediction lines given in Figs. 5.8 and 5.22 of the three trommels, show that the lines of empirical model were closer to the 1:1 or 100 % line of the observed values than those of the semi-empirical model. This indicates its better accuracy in prediction. The empirical model was developed from the actual values of screening inaccuracy. Its relevant measurements, like the weight of tailings, etc., pertained to the material collected at the end of screening process. At the same time, the relevant measurements of the semi-empirical model pertained to the material collected before the completion of screening process. This appeared to be the reasons for the superior accuracy of empirical model.

Among the three trommels, the one having the largest apertures predicted the screening inaccuracy better than the rest. When the aperture size was more, maximum size of the particle that could pass through it was more. Correspondingly, the particles are heavier. It helps these particles, especially of the near-mesh size, to exert a larger downward force while passing through the aperture. This helps these particles to overcome the friction between them and the inside surface of aperture. So, the passage of particles becomes smoother, easier, and more uniform compared to those pertaining to smaller apertures. Perhaps, this resulted in better accuracy in prediction. Based on the above, the major conclusions drawn on the prediction capability of the two models are as given below.

1. The empirical model predicted screening inaccuracy more accurately than the semi-empirical model.
2. Both the models, in general, underestimated the screening inaccuracy.
3. Empirical and semi-empirical models of the trommels of larger apertures predicted screening inaccuracy better than those of smaller apertures.

It was evident from the results and discussion presented in this chapter that, the existing equipments in use in size classifying black pepper were either inefficient or low in output. It showed also that a hexagonal flighted-trommel was capable of producing screening inaccuracies as low as that tolerated by the Agmark Grade Specifications, with a feedstock that has undergone an initial scalping. Further, the empirical model developed in this study could be used to predict screening inaccuracy with reasonable accuracy. It is believed that the results of this study would considerably help the black pepper farmers in realising more returns from their produce. The summary of this study is presented in the chapter that follows.

Chapter 6

SUMMARY AND CONCLUSIONS

Among spices, black pepper (*Piper nigrum* Linn.) is the most sought after spice in the world. It is the dried mature berries of the perennial evergreen vine *Piper nigrum* Linn., and is dark brown to pitch black in colour and nearly globular with a wrinkled surface. It is valued for its culinary, medicinal, aromatic, and cosmetic properties besides being a major commodity for export.

India is considered the 'Land of Spices'. According to the provisional estimates, India earned nearly Rs 140.5 crores in foreign exchange by exporting about 16,700 tonnes of black pepper in 2005-'06. The estimated production was 79,640 metric tonnes from an area of 2,57,020 hectares (Premaja and Manojkumar, 2007).

In the domestic and international markets, many types and grades of black pepper, each with a specific name and quality, are accepted. The Government of India has prescribed, under the provisions of the Agricultural Produce (Grading and Marking) Act 1937, three grades of black pepper on the basis of size. The black pepper classified under this must be capable of being retained on screens having circular apertures of the designated diameters of 4.75 mm for one grade, and 4.25 and 4.00 mm respectively for the other two. The maximum tolerance allowed for lower sizes in a grade is only five per cent.

The two equipment commonly used in size classifying of black pepper in India are the manually-operated flat tray sieves and the oscillating flat screens. Outputs in the case of these are very low if more accuracy is insisted upon. As observed by Turnquist and Porterfield (1967) and Feller *et al.* (1986), the oscillating flat screens are very inefficient in sizing. This is mainly because of the problems associated with clogging. The screen motion which reduces clogging hinders particle passage through the apertures, and which improves particle passage causes clogging; both leading to screening inaccuracy. Special devices are attached to some oscillating flat screens for removing, at regular intervals, the materials clogging the apertures. In certain cases, the oscillating flat screens are stopped at regular intervals and the particles clogging the apertures manually removed by tapping the screen element from below. This leads to frequent interruptions in the process.

Screening inaccuracy indicates the fraction of undersize material in the tailings. It indicates the inaccuracy of screening. *Tailings* are the materials discharged from the screen through its outlet for oversize materials and may contain the undersize materials that have become unsuccessful in passing through the perforations. The undersize materials are known also as *fines*.

Badger and Banchero (1982) and Bosoi *et al.* (1990) reported of using trommels or rotary drum screens in size classifying. However, application of these in size classifying of black pepper was not seen reported in the literature. Preliminary studies showed that better screening accuracy is attainable with a rotary hexagonal flighted-trommel. It also indicated that clogging was not cumulative. Similarly, in line with the earlier studies reported, parameters like speed of rotation of the trommel, feed rate, and feed composition were considered to exert some influence on the performance of trommels. There was, therefore, a need to conduct a systematic study on this equipment to establish its utility in size classifying black pepper and to provide useful data for its design and operation. Besides, a semi-empirical model to predict, with reasonable accuracy, the screening inaccuracy of a trommel was also felt needed for its designers and users. In the light of above, a study was undertaken with the following major objectives:

1. **to evaluate the existing methods of size classifying black pepper in India,**
2. **to develop a reliable semi-empirical model for predicting screening inaccuracy of a hexagonal flighted-trommel in size classifying black pepper,**
3. **to investigate the effect of trommel speed, feed rate, and feed composition on screening performance of a hexagonal flighted-trommel in size classifying black pepper and assess the trommel's economic viability in that process, and**
4. **to develop a reliable empirical model for predicting screening inaccuracy of a hexagonal flighted-trommel in size classifying black pepper.**

In order to achieve the objectives, the study was organized under different heads. Brief descriptions of these are presented below.

1. Physical and engineering properties of black pepper

Physical and engineering properties are used to clearly designate agricultural produce, particularly when used for experimental purposes. Besides, information on them was also needed in the design of trommels. The black pepper used in the present study consisted of the commodity collected from twenty different markets in the state of Kerala in India. These were divided into appropriate sample lots and used in the study. The physical properties studied were 1000-grain weight, grain weight, bulk density, moisture content, physical dimensions, sphericity, volume, and specific gravity. Engineering properties studied included angle of repose in piling, coefficient of rolling friction, and coefficient of sliding friction. Some of these were used in the design of experimental set-up.

2. Evaluation of the existing methods of size classifying black pepper

Manual sieving of black pepper, carried out on a farm, using a flat tray screen (size: 0.9 x 0.6 m; and aperture diameter: 4.25 mm) was evaluated. The time taken to reduce screening inaccuracy to 20, 15, 10, and 5 per cent (with a unilateral tolerance: –2 %) for sample lots of 2 kg of black pepper was noted to determine output. The unit cost of sieving was also determined.

Similarly, an oscillating flat screen (size: 0.9 x 0.6 m; and aperture diameter: 4.25 mm) was also assessed at different oscillating frequencies (6, 8, and 12 Hz), feed rates (150, 250, and 350 kg/h), and feed compositions (0.330 and 0.675). Screening inaccuracy and clogging index were determined.

3. Development of a semi-empirical model for prediction of screening inaccuracy of a hexagonal flighted-trommel and assessment of its accuracy of prediction

A semi-empirical model was developed based on the velocity of transport of particles in the axial direction of trommel and the material hold-up in it. Material hold-up in the presence of passage of fines through apertures was also considered. The two correction factors required in the model were determined from a measurement of actual material hold-up. The accuracy of prediction was assessed by comparing the predicted values with the experimental results and noting the percentage deviation and the correlation.

4. Investigation of the effect of trommel speed, feed rate, and feed composition on screening performance of a hexagonal flighted-trommel

Three hexagonal trommels of aperture diameters, 4.00, 4.25, and 4.75 mm were fabricated. These were 1000 mm long and each side of the hexagon measured 100 mm. Effective length of the perforated portion was 900 mm. A hopper of capacity 0.025 m^3 and having a regulator gate supplied feedstock to the trommel at the rates of 60, 90, 120 and 150 kg/h. The trommel inclination was fixed at 4^0. A 0.5-hp electric motor coupled through a reduction gearbox was used to drive the trommel at speeds of 10, 15, 20, and 25 rev/min. The feedstock for experiments was prepared by maintaining the fraction of oversize material in the feed at the four levels of 0.150, 0.325, 0.500, and 0.675. Remaining were undersize materials or fines.

A 3-factor factorial experiment in a Completely Randomized Design was adopted for each of the trommels. Independent variables and their levels of treatment were: Feed rate [60, 90, 120, and 150 kg/h]; Trommel speed [10, 15, 20, and 25 rev/min.]; and Feed composition, i.e., *fraction of oversize black pepper in feed by weight* [0.150, 0.325, 0.500, and 0.675]. Dependent variables were: (i) Screening inaccuracy, (ii) Zone-wise screening percentage of fines, (iii) Clogging index, and (iv) Power consumption. Each of the 64 treatments was replicated six times. Unit cost of sizing was also determined.

In this study, the trommel screened 2 kg of feedstock in each experiment. Tailings collected at the outlet were analysed for the quantity of fines in it to determine screening inaccuracy. Weight of the berries clogging the apertures and the power requirement were also noted for their respective analyses. The experiments were continued further and the material hold-up measured for verification of the semi-empirical model. Also, screening inaccuracies and values of correction factors were experimentally determined separately for verifying the validity of the models developed. The experimental data on screening inaccuracy, clogging index, and power requirement were analysed statistically.

5. Development of empirical models for predicting screening inaccuracy of a hexagonal flighted-trommel

Empirical models for predicting screening inaccuracy in terms of feed composition, feed rate, and trommel speed were developed through the multiple regression technique. The accuracy of prediction was assessed by comparing the predicted values with the experimental results and noting the percentage deviation and the correlation.

The observations during the experiments and the analyses of the data have led to a number of findings. The salient findings among them are listed below.

Salient Findings

The salient findings of this study are presented below under their respective heads.

A. Manually-operated flat tray screen

1. In sizing black pepper in the manually operated flat tray sieve studied, outputs at the screening inaccuracies of 20, 15, 10, and 5 % (unilateral tolerance, –2%) were respectively 66.7, 41.3, 25.6, and 18.2 kg/man-h. The corresponding unit costs of sieving were respectively Rs 0.38, 0.61, 0.99, and 1.38 per kilogram. So, lower screening inaccuracies, as tolerated by the Agmark Grade Specifications, could be achieved only at a higher unit cost and at the expense of the output. Further, optimum output and optimum size differentiation could not be achieved simultaneously,

B. Oscillating flat screen

1. In sizing black pepper in the oscillating flat screen studied, lower screening inaccuracies were produced at the feed composition of 0.675 than 0.330. The minimum screening inaccuracy observed at the feed composition of 0.675 was 15.6 per cent.

2. The feed rate, 250 kg/h, was better than 150 and 350 kg/h for obtaining lower screening inaccuracies. At the same time, for an ungarbled feedstock collected freshly from the trader, even this feed rate produced screening inaccuracies as high as 32.6-48.7 per cent within 120 s from the commencement of screening.

3. The oscillation frequency, 8 Hz, was better than 6 and 12 Hz for obtaining lower screening inaccuracies because lower frequency encouraged clogging whereas higher frequency prevented particle passage through an aperture that was even open.

4. Though the feed rate, 150 kg/h, was better than 250 and 350 kg/h for obtaining lower clogging indices, the feed rate 250 kg/h, was beneficial for more accurate sizing.

5. The increasing of oscillation frequency reduced clogging through the increased inertia forces. Though the oscillation frequency, 12 Hz, was better than 6 and 8 Hz for obtaining lower clogging indices, the oscillation frequency of 8 Hz was advantageous for obtaining better size grading.

6. The lengthening of screening duration increased the clogging index in an oscillating flat screen because more and more particles entered the apertures and remained

trapped with the passage of time. Hence, clogging was cumulative with respect to screening duration.

7. The output suitable for producing lower screening inaccuracies in the oscillating flat screen studied was 250 kg/h.

C. Semi-empirical model for predicting screening inaccuracy of a hexagonal flighted-trommel

1. The screening inaccuracy (S_i) of a hexagonal trommel could be predicted with reasonable accuracy, from the total feed rate (F_T), feed rate of undersize material (F_U), and the correction factors (C_o and C_u), using the proposed semi-empirical model given below:

$$S_i = 1 - \left[\frac{C_o(F_T - F_U)}{C_o(F_T - F_U) + C_U F_U} \right] \qquad ...(3.22)$$

2. The correlation between the predicted and the observed values of screening inaccuracy was significant with R' ≥ 0.9 for all the three hexagonal trommels. The percentage deviations between the two values varied from –34.7 to 44.5 per cent.

3. The correction factors, C_o and C_u, in Eqn (3.22), could be predicted from the feed composition (F_C), total feed rate (F_T), and trommel speed (N), with a coefficient of determination ($R^2 \geq 0.85$), using the models given below for the three trommels:

For the trommel of 4.00-mm aperture diameter

$$C_o = 0.4057 + 0.00048F_T - 0.00211N \qquad ...(5.11)$$

$$C_u = -0.0337 + 0.3523F_C - 0.4704F_C^2 + 0.00062F_C F_T + 0.000013F_T N \qquad ...(5.12)$$

For the trommel of 4.25-mm aperture diameter

$$C_o = 0.4087 + 0.00042F_T - 0.00224N \qquad ...(5.13)$$

$$C_u = -0.0311 + 0.2939F_C - 0.4092F_C^2 + 0.00097F_C F_T + 0.000011F_T N \qquad ...(5.14)$$

For the trommel of 4.75-mm aperture diameter

$$C_o = 0.4034 + 0.00048F_T - 0.00219N \qquad ...(5.15)$$

$$C_u = -0.0338 + 0.3329F_C - 0.4454F_C^2 + 0.00081F_C F_T + 0.000014F_T N \qquad ...(5.16)$$

4. Based on the F-values, all the relationships were significant at 1 per cent level. Besides, the high values of correlation coefficient (R'), between the observed and the predicted values of correction factors, suggested that the prediction was reasonably accurate, for the three trommels. Grand means of the percentage deviation of C_o, considering all the three trommels, lied in the range from –4.9 to 8.9 per cent. . However, in respect of C_u, the deviations were larger and in the range from –25.3 to 26.6 per cent.

D. Screening inaccuracy of a hexagonal flighted-trommel

1. The feed composition, 0.675, produced screening inaccuracies tolerated by the Agmark Grade Specifications, compared to the feed compositions, 0.150, 0.325, and 0.500.

2. Generally, increasing of the feed rate and the trommel speed was detrimental to accurate sizing. The feed rates, 60 and 90 kg/h, were better than 120 and 150 kg/h for obtaining lower screening inaccuracies. They produced screening inaccuracies below 5 per cent.

3. Similarly, the trommel speeds, 10 and 15 r/min, were better than 20 and 25 r/min for obtaining lower screening inaccuracies. Screening inaccuracies lower than five percent were produced at these speeds.

4. The design made in this study was able to make the trommel produce screening inaccuracies below 5 per cent for a black pepper feedstock, which had undergone an initial scalping.

5. All the above were applicable equally to the trommels of aperture diameters, 4.00, 4.25, and 4.75 mm, irrespective of their aperture size.

E. Zone-wise screening percentage of fines in a hexagonal flighted-trommel

1. In general, higher feed compositions and lower feed rates produced higher zone-wise screening percentage of fines, whereas the higher trommel speed, did not exhibit pronounced effect on the zone-wise screening percentage of fines.

2. Zone-wise screening percentage, generally, decreased with the increase in the zone's distance from the inlet end of trommel. As much as 50 per cent of the undersize

material in the feedstock got separated in the first zone itself, especially at higher feed composition. The zone-wise screening percentage of fines was, mainly, dependent on the quantity of undersize material on the screen.

F. Clogging index of a hexagonal flighted-trommel

1. In general, higher feed compositions produced higher clogging indices in the trommel of small apertures whereas it was the lower feed compositions which produced higher clogging indices in the trommel of larger apertures. Higher feed rates too led to, generally, higher clogging indices in trommels. Trommel speed, in general, did not vary the clogging index considerably in the trommels, though in some cases it reduced clogging at higher speeds. The highest value among the grand means of clogging indices of the three trommels was only 0.18 per cent, which was that of the trommel of smallest apertures. The maximum and minimum were 0.02 and 0.25 per cent respectively. Further, clogging was not of cumulative nature with respect to time.

G. Power requirement of a hexagonal flighted-trommel

1. Increase in the feed rate and the trommel speeds increased the power requirement of the trommels. The maximum power requirement of 1.9 W occurred at the highest feed rate of 150 kg/h and the highest speed of 25 r/min. But, it needed only 0.7-1.1 W when operating to produce screening inaccuracies below 5 per cent. Therefore, the power requirement of the trommel was very low. Similarly, the minimum was at the lowest of the speeds.

H. Cost of size classifying in a hexagonal flighted-trommel

1. The unit cost of sieving black pepper with a hexagonal sieve was only Rs 0.40 per kilogram at the feed rate of 90 kg/h. This is cheaper compared to manual sieving.

I. Empirical models for predicting screening inaccuracy of a hexagonal flighted-trommel

1. The multiple regression models developed for predicting screening inaccuracy in terms of feed composition, feed rate, and trommel speed of the three trommels were:

    1. For the trommel of 4.00-mm aperture diameter

$$S_i = 30.3 - 61.257F_C + 0.1005F_T + 0.409N \qquad \text{...(5.52)}$$

2. For the trommel of 4.25-mm aperture diameter

$$S_i = 29.2 - 54.682F_C + 0.0923F_T + 0.344N \quad ...(5.53)$$

3. For the trommel of 4.75-mm aperture diameter

$$S_i = 30.6 - 56.632F_C + 0.1075F_T + 0.279N \quad ...(5.54)$$

2. High F values indicated of the significance of the relationships at 1 per cent level. The high values of coefficient of determination ($R^2 \geq 0.97$) showed that these models could predict screening inaccuracy with reasonable accuracy. The grand means of their percentage deviation; among all the three trommels; varied from –60.6 to 121.9 per cent. Barring these two extreme values, the next extreme values were -57.3 and 74.4 per cent.

J. Comparison of the semi-empirical and empirical models

1. The empirical model predicted screening inaccuracy fairly well, though the two extreme values were quite large (–60.6 to 121.9 per cent) for the three trommels. At the same time, the extreme values (–34.7 to 44.5 per cent) given by the semi-empirical model were comparatively closer to the observed values. Further, both the models, by and large, underestimated the screening inaccuracies. A comparison of the prediction lines of the three trommels showed that the lines of empirical models were closer to the 1:1 or 100 % line of the observed values than those of the semi-empirical model. Among the three trommels, the one having the largest apertures predicted the screening inaccuracy better than the rest.

K. Comparative performance of manually-operated flat tray sieve, oscillating flat screen and hexagonal flighted-trommel

1. Though manually-operated sieve and hexagonal flighted-trommel gave mean screening inaccuracies below the prescribed 5 %, the least of those produced by the oscillating flat screen was as high as 32.6 %. At the same time, the trommel could produce the said levels even at a capacity of 81.8 kg/W-h as compared to the 0.24 kg/W-h of the manually-operated sieve. Corresponding unit cost of sieving for a trommel was Rs 0.40 per kilogram as against Rs 1.38 per kilogram for the manually-operated sieve. As the oscillating flat screen did not give tolerable levels of screening inaccuracy, its performance in terms of capacity and unit cost was not compared.

Based on the foregoing, the major conclusions are as given below.

Salient Conclusions

1. The data generated on the properties of black pepper provided useful information on its physical and engineering properties besides confirming its suitability as a feedstock in this study. Data on bulk density, 1000-grain weight, angle of repose, etc. could find use in the design of trommel hopper, tail chute, guide chute, etc.
2. In sizing black pepper in the manually operated flat tray sieve studied, lower screening inaccuracies could be achieved only at the expense of the output. The output at the screening inaccuracy levels tolerated by the Agmark Grade Specifications was 18.2 kg/man-h. The corresponding unit cost of sieving was Rs 1.38 per kilogram. Therefore, sizing of black pepper with a manually operated sieve led to not only low capacity but also high unit cost.
3. In sizing black pepper, the oscillating flat screen studied was incapable of reducing the screening inaccuracy to the levels tolerated by the Agmark Grade Specifications. As an overall effect, the increasing of feed rate, oscillation frequency, and screening duration of the oscillating flat screen was detrimental to accurate size grading due to the overpopulation of particles on the screen surface, deleterious screen motion, and cumulative clogging respectively. The combination of feed composition (0.675), feed rate (250 kg/h), and the oscillation frequency (8Hz) produced the lowest screening inaccuracy of 15.6 per cent in the oscillating flat screen.
4. The lengthening of screening duration increased the clogging index in the oscillating flat screen. Hence, clogging was cumulative in nature. Clogging was a major problem in size classifying black pepper with the existing equipments studied.
5. The screening inaccuracy of a hexagonal flighted-trommel in sizing black pepper could be predicted with reasonable accuracy using the proposed semi-empirical model in terms of feed composition, feed rate, and trommel speed. The correction factors, Co and Cu, in the semi-empirical model could also be predicted with reasonable accuracy using the proposed empirical models.
6. The design made in this study was sound enough to make the hexagonal flighted-trommels capable of reducing the screening inaccuracy to the levels of 5 per cent and below tolerated by the Agmark Grade Specifications, provided the ungarbled feedstock was subjected to an initial scalping so that the feedstock did not contain large quantity of undersize particles. Lower feed rates from 60 to 90 kg/h and the trommel speeds from 10 to 15 r/min were necessary for achieving this.

7. As an overall effect, increasing of the feed rate and the trommel speed was detrimental to accurate sizing because their increase raised the screening inaccuracy due to overpopulation of particles in the trommel and the deleterious screen motion. In general, higher feed compositions and lower feed rates produced higher zone-wise screening percentage of fines, whereas the changes in trommel speed, did not exhibit pronounced effect on the zone-wise screening percentage of fines.
8. Higher zone-wise screening percentage of fines in the first few zones of the trommels were due to the quicker sifting of large quantity of particles too small for the apertures. Zone-wise screening percentage, generally, decreased with the increase in the zone's distance from the inlet end of trommel.
9. Higher feed rates and feed compositions led to, generally, higher clogging indices in trommels. Increasing of trommel speed, in general, did not vary the clogging index considerably. Unlike the existing equipment studied, clogging in a trommel was not cumulative with respect to time due to the self-cleaning characteristics. The maximum and minimum were 0.02 and 0.25 per cent respectively. Therefore, clogging was not a major problem with the trommels.
10. The trommels required only 0.7-1.1 W of power when producing screening inaccuracies below 5 per cent. So, power requirement of the trommel was very low.
11. The empirical models developed for predicting screening inaccuracy of the trommels in terms of feed composition, feed rate, and trommel speed had reasonably high degrees of accuracy. The empirical models predicted screening inaccuracy more accurately than the semi-empirical model.
12. The performance of the three trommels studied, in general, were alike irrespective of the size of apertures. The unit cost of sieving black pepper with a hexagonal flighted-trommel was only Rs 0.40 per kilogram at the feed rate of 90 kg/h.

Based on the above, it is finally concluded that the designed hexagonal flighted-trommel is a better alternative to the existing equipment used in size classifying black pepper in India. Lower screening inaccuracies, as tolerated by the Agmark Grade Specifications, are attainable with these. It is hoped that the research findings presented in the thesis would be of benefit to the farmers and traders as it shall enable them to do the size classification of black pepper more efficiently, cheaply, and consuming less power, using hexagonal flighted-trommels.

SUGGESTIONS FOR FUTURE WORK

In the course of this investigation it was felt that a number of points require further investigations. These are suggested for further work:

1. Investigation on the effect of the following on screening inaccuracy, and clogging index of trommels:
   - particle orientation in the aperture
   - size of wrinkles and other irregular projections on the surface of black pepper
   - attrition of interlocking projections
   - vibration of screen element at the location of aperture
   - weight of particles
   - trommel inclination
   - particle diameter
   - length of screen
   - combined motion of rotation and oscillation
   - width of flight
2. Development of a method for facilitating the passage of near-mesh particles through the apertures.
3. Development of a battery of hexagonal trommels for increasing the capacity of the processing plant and for taking more advantage of the power supply system.
4. Improvement of the semi-empirical model for enhancing its accuracy of prediction.
5. Studies for establishing the extent to which each assumption in the semi-empirical model is reasonable.

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Specifications of the electric motor and its control system

Electric motor (D C shunt motor)

HP	: 0.5	RPM : 1750 r/min
Volts	: 115 V	Amps : 4.0 A
Field volts	: 115 V	Amps : 5.0 A
Winding	: shunt	
Rating	: 70^0 C continuous	

Transformer

Primary volts	: 240/480 V	Cycles : 50/60 Hz
Secondary volts	: 120/240 V	KVA : 0.750 kVA

Controller (0.5-hp motor speed control)

Nominal hp	: 0.5		
Power requirements			
Volts	: 115 V	Cycles : 50/60 Hz	Phase : 1
Maximum Amps	: 6.0 A		

Motor requirements

Direct current	: 115 V (shunt or compound)
Armature current	: 4.5 A (maximum)
Field current	: 6.0 A (maximum)

Table B-1 Moisture content of black pepper

Sl. No.	Weight*			Moisture Content*	
	Wet Sample (g)	Moisture (g)	Dry Sample (g)	w.b. (%)	d.b. (%)
1	40.223	3.860	36.363	9.6	10.6
2	40.348	3.785	36.563	9.4	10.4
3	40.757	3.474	37.283	**8.5**	**9.3**
4	40.322	3.538	36.784	8.8	9.6
5	40.573	3.819	36.754	9.4	10.4
6	40.146	3.982	36.164	**9.9**	**11.0**
7	40.392	3.601	36.791	8.9	9.8
8	40.562	4.010	36.552	9.9	11.0
9	40.320	3.955	36.365	9.8	10.9
10	40.305	3.851	36.454	9.6	10.6
11	40.812	3.680	37.132	9.0	9.9
12	40.634	3.740	36.894	9.2	10.1
13	40.735	3.850	36.885	9.5	10.4
14	40.058	3.424	36.634	8.5	9.3
15	40.328	3.694	36.634	9.2	10.1
16	40.587	3.591	36.996	8.8	9.7
17	40.627	3.603	37.024	8.9	9.7
18	40.338	3.481	36.857	8.6	9.4
19	40.967	3.559	37.408	8.7	9.5
20	40.198	3.456	36.742	8.6	9.4
			Grand Mean	**9.1**	**10.1**
			Standard Deviation	***0.47***	***0.58***

* *Mean of 5 replications*

Table B-2 Size and sphericity of black pepper

Sl.No.	Largest Intercept* (a) mm	Largest Intercept Normal to (a)* (b) mm	Largest Intercept Normal to (a) & (b)* (c) mm	Sphericity* $\frac{(abc)^{1/3}}{a}$ (-)
1	**3.89**	3.81	3.79	0.98
2	4.56	4.02	4.01	**0.92**
3	4.41	4.22	4.2	0.97
4	3.91	3.83	3.83	**0.99**
5	4.06	**3.67**	**3.65**	0.93
6	4.37	4.09	4.07	0.96
7	4.48	3.96	3.96	0.92
8	4.96	4.63	4.6	0.95
9	4.75	4.61	4.59	0.98
10	4.27	3.96	3.95	0.95
11	**5.16**	4.92	**4.92**	0.97
12	4.63	4.42	4.41	0.97
13	4.33	4.17	4.17	0.98
14	4.44	4.21	4.2	0.96
15	4.63	4.36	4.34	0.96
16	5.15	**4.93**	4.92	0.97
17	5.03	4.89	4.87	0.98
18	4.73	4.31	4.31	0.94
19	3.97	3.81	3.78	0.97
20	5.02	4.87	4.86	0.98
Grand Mean	**4.54**	**4.28**	**4.27**	**0.96**
Standard Deviation	***0.4***	***0.41***	***0.41***	***0.02***

** Mean of 10 replications*

Table B-3 Volume and specific gravity of black pepper

Density of water = 0.995 g/cm^3 at 32^0 C at 1 atmospheric pressure

Sl.No	Volume of 100 Berries in Pycnometer*	Weight of 100 Berries*	Volume of a Berry*	Specific Gravity*
	V_{100}	W_{100}	V_1	
	cm^3	g	cm^3	(-)
1	5.2	5.4	0.052	1.04
2	5.0	5.3	0.050	1.07
3	**5.8**	**6.3**	**0.058**	1.09
4	3.7	3.9	0.037	1.06
5	4.9	5.6	0.049	1.15
6	**3.6**	4.0	**0.036**	1.12
7	4.5	4.8	0.045	1.07
8	4.8	4.9	0.048	1.03
9	5.1	5.2	0.051	**1.02**
10	3.9	4.4	0.039	1.13
11	4.6	5.2	0.046	1.14
12	4.9	5.5	0.049	1.13
13	5.3	5.8	0.053	1.10
14	4.4	4.7	0.044	1.07
15	3.8	4.3	0.038	1.14
16	3.6	**3.7**	0.036	1.03
17	4.5	5.3	0.045	**1.18**
18	5.4	6.2	0.054	1.15
19	4.8	5.4	0.048	1.13
20	5.5	6.1	0.055	1.11
Grand Mean	**4.7**	**5.1**	**0.047**	**1.10**
Standard Deviation	***0.7***	***0.8***	***0.007***	***0.05***

* *Mean of 5 replications*

Table B-4 Bulk density, 1000-grain weight, and weight per grain of black pepper

Sl.No.	Bulk Density*	1000-Grain Weight*	Weight/Grain*
	kg/m^3	g	g
1	560.8	39.718	0.040
2	580.5	38.898	0.039
3	584.0	38.454	0.038
4	**623.8**	45.136	0.045
5	512.5	47.505	0.048
6	503.5	46.603	0.047
7	590.8	47.339	0.047
8	571.0	46.428	0.046
9	476.5	**36.218**	**0.036**
10	**453.8**	49.214	0.049
11	580.8	53.726	0.054
12	580.6	61.223	0.061
13	564.5	59.728	0.060
14	583.6	55.334	0.055
15	496.2	54.823	0.055
16	547.3	58.614	0.059
17	562.5	**63.711**	**0.064**
18	570.8	55.540	0.056
19	560.7	52.932	0.053
20	588.3	54.684	0.055
Grand Mean	**554.6**	**50.291**	**0.050**
Standard Deviation	***43.4***	***8.02***	***0.008***

* *Mean of 5 replications*

Table B-5 Angle of repose in piling of black pepper

Sl .No	Height of Pile*	Base Diameter of Pile*	Angle of Repose*
	mm	mm	(^{0})
1	65	160	39.1
2	63	164	37.5
3	80	210	37.3
4	80	206	37.8
5	78	212	36.4
6	82	210	38.0
7	82	206	38.5
8	81	230	**35.2**
9	67	186	35.8
10	68	170	38.7
11	67	178	36.9
12	48	124	37.8
13	49	120	39.2
14	73	206	35.3
15	57	142	38.3
16	64	167	37.5
17	53	142	36.7
18	79	191	**39.6**
19	68	164	39.6
20	59	150	38.2
		Mean	**37.7**
		Standard Deviation	***1.32***

* Mean of 5 replications

Table B-6 Coefficients of rolling friction and sliding friction of black pepper on galvanized iron surface

Sl. No.	Rolling			Sliding		
	Grains Rolled	Angle of Tilt	Coefficient	Grains Slid	Angle of Tilt	Coefficient
	(No.)	(^{0})	(-)	(No.)	(^{0})	(-)
1	2	5	0.09	2	15	0.27
2	2	6	0.11	6	16	0.29
3	3	7	0.12	1	17	0.31
4	5	8	0.14	2	18	0.32
5	6	9	0.16	8	19	0.34
6	5	10	0.18	3	20	0.36
7	5	11	0.19	9	21	0.38
8	3	12	0.21	6	22	0.40
9	18	13	0.23	14	23	0.42
10	9	14	0.25	21	24	0.45
11	23	15	0.27	24	25	0.47
12	14	16	0.29	15	26	0.49
13	21	17	0.31	12	27	0.51
14	18	18	0.32	25	28	0.53
15	21	19	0.34	14	29	0.55
16	9	20	0.36	12	30	0.58
17	13	21	0.38	9	31	0.60
18	8	22	0.40	6	32	0.62
19	5	23	0.42	1	33	0.65
20	1	24	0.45	2	34	0.67
21	6	25	0.47	4	35	0.70
22	2	26	0.49	1	36	0.72
23	1	27	0.51	2	37	0.75
24	-	-	-	1	38	0.78
Total	200			200		
	Mean	**16**	**0.29**		**26.5**	**0.51**
Standard Deviation		***6.8***	***0.13***		***7.1***	***0.16***

Table C-1 Output and unit cost of operation of manually-operated flat tray sieve

Quantity sieved per experiment = 2 kg
No. of operators = 2
Labour wages per hour at Kochi = Rs 25/man-h

Lot No.	Screening-Inaccuracy Level[1]	Mean Duration[2]	Output	Unit Cost
	%	s	kg/man-h	Rs/kg
1	20	56.1	64.2	0.39
2		56.1	64.2	0.39
3		50.2	71.7	0.35
		Grand Mean	**66.7**	**0.38**
		S.D.	*4.3*	*0.03*
1	15	93.8	38.4	0.65
2		88.0	40.9	0.61
3		80.5	44.7	0.56
		Grand Mean	**41.3**	**0.61**
		S.D.	*3.2*	*0.05*
1	10	135.8	26.5	0.94
2		162.9	22.1	1.13
3		128.1	28.1	0.89
		Grand Mean	**25.6**	**0.99**
		S.D.	*3.1*	*0.13*
1	5	196.7	18.3	1.37
2		220.9	16.3	1.53
3		179.1	20.1	1.24
		Grand Mean	**18.2**	**1.38**
		S.D.	*1.9*	*0.15*

[1] Unilateral tolerance allowed = -2 % [2] Mean of 6 replications

Table C-2 Screening inaccuracies of oscillating flat screen at various feed compositions, feed rates, oscillation frequencies, and screening durations

Feed Rate	Oscillation Frequency	Replication No.	Screening Inaccuracy, %							
			Feed Composition, (-)							
			0.330				0.675			
			Screening Duration, s							
kg/h	Hz	(-)	60	80	100	120	60	80	100	120
150	6	1	42.1	42.6	41.9	39.4	19.9	20.9	22.3	24.9
		2	37.2	38.6	44.3	43.8	20.6	21.4	21.8	21.4
		3	38.8	43.5	40.6	45.2	18.8	20.2	21.3	22.9
		Mean	**39.4**	**41.6**	**42.3**	**42.8**	**19.8**	**20.8**	**21.8**	**23.1**
	8	1	34.1	34.2	38.4	38.1	19.1	20.8	20.7	22.9
		2	34.6	38.3	39.4	36.6	17.2	19.4	19.5	22.0
		3	36.5	37.2	35.4	40.0	18.8	17.9	19.0	21.6
		Mean	**35.1**	**36.6**	**37.7**	**38.2**	**18.4**	**19.4**	**19.7**	**22.2**
	12	1	*45.7*	*45.9*	*48.4*	*48.2*	29.6	30.2	34.0	34.6
		2	*44.2*	*48.1*	*45.0*	*46.9*	31.7	32.2	32.6	30.8
		3	*42.3*	*46.5*	*45.9*	*47.3*	26.4	27.3	29.3	33.1
		Mean	**44.1**	**46.8**	**46.4**	**47.5**	**29.2**	**29.9**	**32.0**	**32.8**
250	6	1	39.4	37.7	40.2	38.4	17.9	18.1	19.1	21.6
		2	35.1	36.4	37.6	42.6	18.1	18.8	20.3	20.6
		3	34.7	34.6	38.9	37.5	19.7	19.9	19.6	20.0
		Mean	**36.4**	**36.2**	**38.9**	**39.5**	**18.6**	**18.9**	**19.7**	**20.7**
	8	1	34.9	36.6	33.4	35.8	16.9	16.9	18.6	17.8
		2	**32.6**	37.6	34.9	38.7	16.2	17.3	16.9	19.2
		3	35.3	33.7	37.5	37.5	**15.6**	18.1	17.2	18.6
		Mean	**34.3**	**36.0**	**35.3**	**37.3**	**16.2**	**17.4**	**17.6**	**18.5**
	12	1	41.5	45.6	40.7	42.6	29.7	29.4	28.7	31.3
		2	40.9	41.8	45.1	**48.7**	26.7	31.2	30.6	28.1
		3	44.3	40.4	45.5	47.1	25.4	27.5	32.1	30.9
		Mean	**42.2**	**42.6**	**43.8**	**46.1**	**27.3**	**29.4**	**30.5**	**30.1**
350	6	1	43.4	46.8	49.7	51.1	27.9	26.8	30.1	29.6
		2	47.1	42.2	45.6	51.8	24.9	29.4	31.3	32.8
		3	42.5	45.6	48.1	54.4	26.1	27.5	28.2	32.1
		Mean	**44.3**	**44.9**	**47.8**	**52.4**	**26.3**	**27.9**	**29.9**	**31.5**
	8	1	47.1	51.9	52.9	55.9	20.3	22.8	27.5	26.3
		2	50.2	49.4	49.1	51.8	22.8	22.3	25.4	24.7
		3	46.9	46.3	53.6	53.4	21.6	25.1	27.1	26.6
		Mean	**48.1**	**49.2**	**51.9**	**53.7**	**21.6**	**23.4**	**26.7**	**25.9**
	12	1	53.4	54.1	59.2	57.5	34.9	32.9	36.1	35.7
		2	47.7	53.6	54.3	56.4	32.0	33.8	32.4	34.6
		3	52.4	57.7	55.1	60.3	32.6	31.4	35.2	36.7
		Mean	**51.2**	**55.1**	**56.2**	**58.1**	**33.2**	**32.7**	**34.6**	**35.7**

Table C-3 Clogging indices of oscillating flat screen at various feed compositions, feed rates, oscillation frequencies and screening durations

Feed Rate	Oscillation Frequency	Replication No.	Clogging index, %							
			Feed Composition, (-)							
			0.330				0.675			
			Screening Duration, s							
kg/h	Hz	(-)	60	80	100	120	60	80	100	120
150	6	1	3.6	3.7	3.7	6.4	9.2	10.1	12.7	15.2
		2	3.0	4.1	3.8	4.6	8.6	11.3	12.2	16.1
		3	3.1	3.4	4.8	5.5	7.4	9.4	14.5	14.4
		Mean	**3.2**	**3.7**	**4.1**	**5.5**	**8.4**	**10.3**	**13.1**	**15.2**
	8	1	2.6	3.1	3.6	5.4	8.6	8.3	10.4	12.9
		2	2.2	2.8	2.9	3.6	6.5	8.4	12.7	12.1
		3	2.7	3.4	3.2	5.1	7.6	10.5	10.3	15.2
		Mean	**2.5**	**3.1**	**3.2**	**4.7**	**7.6**	**9.1**	**11.1**	**13.4**
	12	1	0.4	1.1	1.0	1.3	3.0	4.3	5.0	6.6
		2	1.0	0.6	1.1	1.4	3.4	3.5	4.4	4.7
		3	0.5	0.7	1.2	1.0	3.5	4.0	4.2	6.1
		Mean	**0.6**	**0.8**	**1.1**	**1.2**	**3.3**	**3.9**	**4.5**	**5.8**
250	6	1	5.5	7.8	9.3	8.7	14.6	16.6	20.1	22.8
		2	4.9	5.4	7.3	10.7	12.3	15.3	21.0	19.5
		3	4.7	6.9	9.7	9.3	13.4	18.1	19.1	21.8
		Mean	**5.0**	**6.7**	**8.8**	**9.6**	**13.4**	**16.7**	**20.1**	**21.4**
	8	1	3.6	6.4	6.1	6.7	11.6	12.4	16.5	19.6
		2	4.6	4.6	5.9	8.7	9.9	14.8	15.2	17.4
		3	4.3	5.9	7.4	7.3	9.2	13.9	17.7	17.9
		Mean	**4.2**	**5.6**	**6.5**	**7.6**	**10.2**	**13.7**	**16.5**	**18.3**
	12	1	0.8	1.4	1.2	1.8	5.2	7.7	8.3	9.8
		2	0.5	1.2	1.3	1.3	6.1	5.2	6.6	10.2
		3	0.8	0.8	1.5	1.3	5.7	6.3	8.7	9.1
		Mean	**0.7**	**1.1**	**1.3**	**1.5**	**5.7**	**6.4**	**7.9**	**9.7**
350	6	1	10.6	15.9	18.9	22.8	21.8	25.7	31.2	36.8
		2	11.7	13.2	17.3	20.1	22.4	27.6	32.2	37.1
		3	8.7	14.3	19.8	20.7	20.3	25.4	32.6	39.3
		Mean	**10.3**	**14.5**	**18.7**	**21.2**	**21.5**	**26.2**	**32.0**	**37.7**
	8	1	7.6	14.2	14.9	17.3	18.8	25.2	31.3	35.7
		2	9.7	11.5	14.3	19.7	20.4	22.7	27.9	34.8
		3	9.2	11.3	17.1	19.1	18.1	23.7	29.1	32.6
		Mean	**8.8**	**12.3**	**15.4**	**18.7**	**19.1**	**23.9**	**29.4**	**34.4**
	12	1	4.9	6.5	5.6	7.6	12.8	15.7	17.4	18.6
		2	4.2	6.0	7.8	9.8	10.6	13.3	17.9	22.1
		3	5.2	5.6	7.3	6.9	10.6	15.8	19.9	21.1
		Mean	**4.7**	**6.0**	**6.9**	**8.1**	**11.3**	**14.9**	**18.4**	**20.6**

Determination of Screening Inaccuracy

(Using Semi-Empirical Model)

Model Calculation

Speed of rotation (N)	= 10 *r/min*
Largest diameter of hexagonal trommel (D_c)	= 0.2 *m*
Angle of tilt from horizontal (α)	= 4^0
(*tan* 4^0 = 0.069927)	
Length of trommel (L)	= 1.0 *m*
Actual oversize-material hold-up (H_{oa})	= 1.473 kg [*From Table* D-1]
Actual mixture hold-up (H_{ma})	= 0.330 kg [*From Table* D-2]
Total feed rate of mixture material (F_T)	= 60 kg/h [*From Table* D-2]
Feed rate of undersize material (F_U)	= 51 kg/h [*From Table* D-2]

Correction factor (C_o) $= \dfrac{120 N D_c \tan\alpha H_{oa}}{F_T L}$ [*From Eqn.* (3.18)]

$$= \frac{120 \times 10 \times 0.2 \times 0.069927 \times 1.473}{60 \times 1}$$

$$= \underline{0.412}$$

Correction factor (C_u) $= \dfrac{120 N D_c \tan\alpha H_{ma} - C_u (F_T - F_U) L}{F_U L}$ [*From Eqn.* (3.18)]

$$= \frac{120 \times 10 \times 0.2 \times 0.069927 \times 0.33 - 0.412 \times 1(60 - 51)}{51 \times 1}$$

$$= \underline{0.036}$$

Screening inaccuracy (S_{ise}) $= \dfrac{C_u F_U \times 100}{C_o (F_T - F_U) + C_u F_U}$ Eqn. (3.22)

$$= \frac{0.036 \times 51 \times 100}{0.412(60 - 51) + 0.036 \times 51}$$

$$= \underline{33.1\ \%}$$

Table D-1 Oversize-berry hold-up and correction factor, C_o, of the semi-empirical model for the three trommels

(Mean of 3 replications)

Trommel Aperture Diameter (D_a)	Feed Rate (F_T)	Trommel Speed (N)	Theoretical Residence Time (T_r)	Hold-up of Oversize Berries: Theoretical (H_o)	Hold-up of Oversize Berries: Actual (H_{oa})	Correction Factor (C_o)
mm	kg/h	r/min	s	kg	kg	(-)
4.00	60	10	214.5	3.575	1.473	0.412
		15	143.0	2.383	0.967	0.406
		20	107.3	1.788	0.712	0.398
		25	85.8	1.430	0.552	0.386
	90	10	214.5	5.363	2.263	0.422
		15	143.0	3.575	1.491	0.417
		20	107.3	2.683	1.094	0.408
		25	85.8	2.145	0.845	0.394
	120	10	214.5	7.150	3.117	0.436
		15	143.0	4.767	2.031	0.426
		20	107.3	3.577	1.484	0.415
		25	85.8	2.860	1.147	0.401
	150	10	214.5	8.938	4.129	0.462
		15	143.0	5.958	2.699	0.453
		20	107.3	4.471	1.971	0.441
		25	85.8	3.575	1.516	0.424
4.25	60	10	214.5	3.575	1.462	0.409
		15	143.0	2.383	0.963	0.404
		20	107.3	1.788	0.708	0.396
		25	85.8	1.430	0.546	0.382
	90	10	214.5	5.363	2.236	0.417
		15	143.0	3.575	1.476	0.413
		20	107.3	2.683	1.080	0.403
		25	85.8	2.145	0.834	0.389
	120	10	214.5	7.150	3.082	0.431
		15	143.0	4.767	1.997	0.419
		20	107.3	3.577	1.455	0.407
		25	85.8	2.860	1.127	0.394
	150	10	214.5	8.938	4.085	0.457
		15	143.0	5.958	2.652	0.445
		20	107.3	4.471	1.931	0.432
		25	85.8	3.575	1.480	0.414
4.75	60	10	214.5	3.575	1.453	0.406
		15	143.0	2.383	0.958	0.402
		20	107.3	1.788	0.706	0.395
		25	85.8	1.430	0.543	0.380
	90	10	214.5	5.363	2.254	0.420
		15	143.0	3.575	1.483	0.415
		20	107.3	2.683	1.088	0.406
		25	85.8	2.145	0.842	0.393
	120	10	214.5	7.150	3.095	0.433
		15	143.0	4.767	2.021	0.424
		20	107.3	3.577	1.462	0.409
		25	85.8	2.860	1.133	0.396
	150	10	214.5	8.938	4.103	0.459
		15	143.0	5.958	2.683	0.450
		20	107.3	4.471	1.964	0.439
		25	85.8	3.575	1.492	0.417

Table D-2 Mixture hold-up, correction factors, and screening inaccuracies (*predicted*) of the semi-empirical model for the three trommels

(Mean of 3 replications)

Feed Composition (F_C)	Feed Rate (F_T)	Trommel Speed (N)	Feed Rate of Undersize Berries (F_U)	Actual Mixture Hold-up (H_{ma}); kg			Correction Factor (C_o) [*from Table D-1*]			Correction Factor (C_u)			Screening Inaccuracy, % Predicted (S_{ise})		
				Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm		
				4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75
(-)	kg/h	r/min	kg/h	kg	kg	kg	(-)	(-)	(-)	(-)	(-)	(-)	%	%	%
0.150	60	10	51.00	0.33	0.322	0.327	0.412	0.409	0.406	0.036	0.034	0.036	33.1	32.0	33.4
		15	51.00	0.221	0.217	0.218	0.406	0.404	0.402	0.037	0.036	0.037	34.1	33.6	34.3
		20	51.00	0.169	0.162	0.164	0.398	0.396	0.395	0.041	0.037	0.038	36.9	34.6	35.3
		25	51.00	0.136	0.127	0.131	0.386	0.382	0.380	0.044	0.037	0.041	39.2	35.4	37.9
	90	10	76.50	0.503	0.489	0.518	0.422	0.417	0.420	0.036	0.034	0.040	32.6	31.6	35.1
		15	76.50	0.341	0.328	0.354	0.417	0.413	0.415	0.039	0.035	0.043	34.6	32.4	37.0
		20	76.50	0.256	0.242	0.263	0.408	0.403	0.406	0.040	0.035	0.044	35.7	33.0	38.0
		25	76.50	0.203	0.191	0.211	0.394	0.389	0.393	0.042	0.036	0.046	37.7	34.4	39.9
	120	10	102.00	0.687	0.668	0.714	0.436	0.431	0.433	0.036	0.034	0.041	31.9	30.9	34.9
		15	102.00	0.449	0.435	0.478	0.426	0.419	0.424	0.036	0.034	0.043	32.4	31.5	36.5
		20	102.00	0.334	0.326	0.364	0.415	0.407	0.409	0.037	0.036	0.048	33.6	33.4	39.9
		25	102.00	0.269	0.277	0.305	0.401	0.394	0.396	0.040	0.045	0.056	36.1	39.3	44.5
	150	10	127.50	0.881	0.873	0.933	0.462	0.457	0.459	0.034	0.034	0.042	29.4	29.7	34.1
		15	127.50	0.594	0.582	0.628	0.453	0.445	0.450	0.037	0.037	0.045	31.6	32.0	36.2
		20	127.50	0.468	0.446	0.476	0.441	0.432	0.439	0.046	0.041	0.048	36.9	35.0	38.3
		25	127.50	0.394	0.372	0.406	0.424	0.414	0.417	0.055	0.049	0.060	42.3	40.1	44.9
0.325	60	10	40.50	0.579	0.587	0.606	0.412	0.409	0.406	0.042	0.047	0.056	17.5	19.3	22.3
		15	40.50	0.391	0.395	0.402	0.406	0.404	0.402	0.048	0.051	0.057	19.7	20.8	22.7
		20	40.50	0.302	0.306	0.297	0.398	0.396	0.395	0.059	0.063	0.056	23.5	24.8	22.7
		25	40.50	0.251	0.239	0.236	0.386	0.382	0.380	0.074	0.064	0.062	28.5	25.8	25.3
	90	10	60.75	0.971	0.984	0.946	0.422	0.417	0.420	0.065	0.071	0.059	24.2	26.1	22.6
		15	60.75	0.653	0.656	0.642	0.417	0.413	0.415	0.070	0.073	0.066	25.9	26.9	24.8
		20	60.75	0.497	0.489	0.498	0.408	0.403	0.406	0.078	0.076	0.080	28.4	28.1	29.0
		25	60.75	0.409	0.391	0.394	0.394	0.389	0.393	0.093	0.083	0.083	32.9	30.7	30.5
	120	10	81.00	1.374	1.381	1.356	0.436	0.431	0.433	0.075	0.079	0.073	26.3	27.6	25.9
		15	81.00	0.923	0.912	0.906	0.426	0.419	0.424	0.082	0.082	0.078	28.6	28.9	27.6
		20	81.00	0.706	0.701	0.691	0.415	0.407	0.409	0.093	0.095	0.090	31.8	32.7	31.4
		25	81.00	0.584	0.565	0.551	0.401	0.394	0.396	0.109	0.103	0.095	36.1	35.2	33.3
	150	10	101.25	1.926	1.902	1.877	0.462	0.457	0.459	0.097	0.096	0.090	30.4	30.4	28.9
		15	101.25	1.302	1.264	1.246	0.453	0.445	0.450	0.106	0.100	0.093	32.7	31.8	30.0
		20	101.25	0.994	0.945	0.961	0.441	0.432	0.439	0.117	0.106	0.108	35.5	33.8	33.8
		25	101.25	0.821	0.755	0.798	0.424	0.414	0.417	0.136	0.114	0.130	40.0	36.4	39.3

(continued)

D-2 ...continued...

Feed Composition (F_C)	Feed Rate (F_T)	Trommel Speed (N)	Feed Rate of Undersize Berries (F_U)	Actual Mixture Hold-up (H_{ma}); kg			Correction Factor (C_o) [*from Table D-1*]			Correction Factor (C_u)			Screening Inaccuracy, % Predicted (S_{ise})		
				Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm		
				4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75
(-)	kg/h	r/min	kg/h	kg	kg	kg	(-)	(-)	(-)	(-)	(-)	(-)	%	%	%
0.500	60	10	30.00	0.811	0.804	0.816	0.412	0.409	0.406	0.042	0.041	0.051	9.3	9.1	11.2
		15	30.00	0.537	0.531	0.544	0.406	0.404	0.402	0.045	0.042	0.055	10.0	9.4	12.0
		20	30.00	0.399	0.391	0.409	0.398	0.396	0.395	0.048	0.042	0.063	10.8	9.6	13.8
		25	30.00	0.315	0.306	0.323	0.386	0.382	0.380	0.055	0.046	0.072	12.5	10.7	15.9
	90	10	45.00	1.271	1.263	1.298	0.422	0.417	0.420	0.052	0.055	0.065	11.0	11.7	13.4
		15	45.00	0.849	0.838	0.862	0.417	0.413	0.415	0.058	0.056	0.068	12.2	11.9	14.1
		20	45.00	0.633	0.639	0.649	0.408	0.403	0.406	0.064	0.074	0.079	13.6	15.5	16.3
		25	45.00	0.499	0.508	0.519	0.394	0.389	0.393	0.071	0.085	0.091	15.3	17.9	18.8
	120	10	60.00	1.794	1.824	1.861	0.436	0.431	0.433	0.066	0.080	0.088	13.1	15.7	16.9
		15	60.00	1.185	1.202	1.235	0.426	0.419	0.424	0.071	0.086	0.095	14.3	17.0	18.3
		20	60.00	0.884	0.896	0.915	0.415	0.407	0.409	0.080	0.095	0.103	16.2	18.9	20.1
		25	60.00	0.717	0.731	0.746	0.401	0.394	0.396	0.100	0.118	0.126	20.0	23.0	24.1
	150	10	75.00	2.457	2.433	2.484	0.462	0.457	0.459	0.088	0.088	0.097	16.0	16.1	17.4
		15	75.00	1.641	1.623	1.663	0.453	0.445	0.450	0.098	0.100	0.109	17.8	18.3	19.5
		20	75.00	1.231	1.21	1.246	0.441	0.432	0.439	0.110	0.110	0.119	20.0	20.3	21.3
		25	75.00	0.986	0.973	1.022	0.424	0.414	0.417	0.128	0.131	0.155	23.2	24.0	27.1
0.675	60	10	19.50	1.036	1.029	1.021	0.412	0.409	0.406	0.036	0.037	0.036	4.0	4.2	4.1
		15	19.50	0.682	0.679	0.674	0.406	0.404	0.402	0.037	0.038	0.036	4.2	4.3	4.1
		20	19.50	0.504	0.501	0.498	0.398	0.396	0.395	0.041	0.041	0.038	4.7	4.7	4.4
		25	19.50	0.394	0.394	0.386	0.386	0.382	0.380	0.046	0.055	0.042	5.4	6.5	5.1
	90	10	29.25	1.593	1.575	1.587	0.422	0.417	0.420	0.038	0.039	0.039	4.2	4.3	4.3
		15	29.25	1.053	1.042	1.048	0.417	0.413	0.415	0.040	0.040	0.041	4.4	4.5	4.5
		20	29.25	0.778	0.771	0.785	0.408	0.403	0.406	0.045	0.049	0.059	5.0	5.5	6.5
		25	29.25	0.615	0.605	0.619	0.394	0.389	0.393	0.065	0.061	0.073	7.3	7.0	8.2
	120	10	39.00	2.236	2.246	2.253	0.436	0.431	0.433	0.057	0.072	0.071	5.9	7.4	7.3
		15	39.00	1.469	1.461	1.481	0.426	0.419	0.424	0.063	0.074	0.076	6.6	7.8	7.9
		20	39.00	1.081	1.075	1.086	0.415	0.407	0.409	0.068	0.081	0.086	7.3	8.7	9.2
		25	39.00	0.846	0.851	0.857	0.401	0.394	0.396	0.077	0.098	0.100	8.5	10.7	10.8
	150	10	48.75	2.996	3.024	3.031	0.462	0.457	0.459	0.072	0.093	0.091	7.0	8.9	8.7
		15	48.75	1.976	1.992	1.998	0.453	0.445	0.450	0.080	0.105	0.098	7.8	10.2	9.5
		20	48.75	1.458	1.486	1.489	0.441	0.432	0.439	0.088	0.127	0.114	8.8	12.4	11.1
		25	48.75	1.149	1.167	1.157	0.424	0.414	0.417	0.109	0.146	0.131	11.0	14.5	13.1

End

Table D-3 Oversize-berry hold-up and correction factor, C_o (observed, predicted, and their percentage deviation) of the semi-empirical model for the three trommels

Trommel Aperture Diameter (D_a)	Feed Rate (F_T)	Trommel Speed (N)	Theoretical Residence Time (T_r)	Hold-up of Oversize Berries: Theoretical (H_o)	Hold-up of Oversize Berries: Actual (H_{oa})	Correction Factor, Co: Observed	Correction Factor, Co: Predicted	Correction Factor, Co: Deviation
mm	kg/h	r/min	s	kg	kg	(-)	(-)	(%)
4.00	60	10	214.5	3.575	1.466	0.410	0.413	-0.8
		15	143.0	2.383	0.956	0.401	0.403	-0.4
		20	107.3	1.788	0.721	0.403	0.392	2.7
		25	85.8	1.430	0.526	0.368	0.382	-3.8
	90	10	214.5	5.363	2.234	0.417	0.428	-2.7
		15	143.0	3.575	1.537	0.430	0.417	2.9
		20	107.3	2.683	1.135	0.423	0.407	3.9
		25	85.8	2.145	0.886	0.413	0.396	4.1
	120	10	214.5	7.150	3.136	0.439	0.442	-0.8
		15	143.0	4.767	2.155	0.452	0.432	4.5
		20	107.3	3.577	1.524	0.426	0.421	1.2
		25	85.8	2.860	1.213	0.424	0.411	3.2
	150	10	214.5	8.938	4.031	0.451	0.457	-1.2
		15	143.0	5.958	2.588	0.434	0.446	-2.7
		20	107.3	4.471	1.999	0.447	0.436	2.6
		25	85.8	3.575	1.567	0.438	0.425	3.1
4.25	60	10	214.5	3.575	1.491	0.417	0.412	1.3
		15	143.0	2.383	0.965	0.405	0.400	1.1
		20	107.3	1.788	0.708	0.396	0.389	1.7
		25	85.8	1.430	0.569	0.398	0.378	5.0
	90	10	214.5	5.363	2.204	0.411	0.424	-3.2
		15	143.0	3.575	1.469	0.411	0.413	-0.5
		20	107.3	2.683	1.117	0.416	0.402	3.5
		25	85.8	2.145	0.894	0.417	0.391	6.3
	120	10	214.5	7.150	3.139	0.439	0.437	0.5
		15	143.0	4.767	2.098	0.440	0.426	3.3
		20	107.3	3.577	1.556	0.435	0.414	4.8
		25	85.8	2.860	1.198	0.419	0.403	3.8
	150	10	214.5	8.938	4.129	0.462	0.449	2.7
		15	143.0	5.958	2.705	0.454	0.438	3.5
		20	107.3	4.471	1.972	0.441	0.427	3.2
		25	85.8	3.575	1.480	0.414	0.416	-0.4
4.75	60	10	214.5	3.575	1.398	0.391	0.410	-4.9
		15	143.0	2.383	0.984	0.413	0.399	3.3
		20	107.3	1.788	0.762	0.426	0.388	8.9
		25	85.8	1.430	0.561	0.392	0.377	3.8
	90	10	214.5	5.363	2.236	0.417	0.425	-1.9
		15	143.0	3.575	1.423	0.398	0.414	-3.9
		20	107.3	2.683	1.097	0.409	0.403	1.5
		25	85.8	2.145	0.886	0.413	0.392	5.1
	120	10	214.5	7.150	3.189	0.446	0.439	1.6
		15	143.0	4.767	1.993	0.418	0.428	-2.4
		20	107.3	3.577	1.434	0.401	0.417	-4.1
		25	85.8	2.860	1.167	0.408	0.406	0.4
	150	10	214.5	8.938	4.174	0.467	0.454	2.9
		15	143.0	5.958	2.693	0.452	0.443	2.1
		20	107.3	4.471	2.007	0.449	0.432	3.9
		25	85.8	3.575	1.466	0.410	0.421	-2.6

Means of 3 replications

Table D-4 Mixture hold-up and correction factors, C_u (observed, predicted, and their percentage deviation) of the semi-empirical model for the three trommels

(Mean of 3 replications)

Feed Composition (F_C)	Feed Rate (F_T)	Trommel Speed (N)	Feed Rate of Undersize Berries (F_U)	Actual Mixture Hold-up (H_{me}) (kg) Aperture Diameter, mm 4.00	4.25	4.75	Predicted Correction Factor (C_o) [from Table D-3] Aperture Diameter, mm 4.00	4.25	4.75	Correction Factor (C_u) Aperture Diameter, 4.00 mm Observed	Predicted	Deviation	Aperture Diameter, 4.25 mm Observed	Predicted	Deviation	Aperture Diameter, 4.75 mm Observed	Predicted	Deviation
(-)	kg/h	r/min	kg/h	kg	kg	kg	(-)	(-)	(-)	(-)	(-)	(%)	(-)	(-)	(%)	(-)	(-)	(%)
0.150	60	10	51.00	0.297	0.291	0.302	0.413	0.412	0.410	0.025	0.022	11.5	0.023	0.019	17.4	0.027	0.022	19.2
0.150	60	15	51.00	0.199	0.205	0.192	0.403	0.400	0.399	0.027	0.026	4.8	0.031	0.022	26.6	0.024	0.026	-7.0
0.150	60	20	51.00	0.162	0.147	0.158	0.392	0.389	0.388	0.037	0.030	20.5	0.028	0.026	8.5	0.035	0.030	14.8
0.150	60	25	51.00	0.129	0.119	0.124	0.382	0.378	0.377	0.039	0.034	13.2	0.031	0.029	7.1	0.035	0.034	2.8
0.150	90	10	76.50	0.495	0.497	0.508	0.428	0.424	0.425	0.033	0.029	13.5	0.034	0.027	21.7	0.036	0.030	18.8
0.150	90	15	76.50	0.341	0.328	0.354	0.417	0.413	0.414	0.039	0.034	10.6	0.035	0.032	9.5	0.043	0.036	17.3
0.150	90	20	76.50	0.267	0.236	0.277	0.407	0.402	0.403	0.045	0.040	11.1	0.033	0.037	-12.3	0.050	0.042	16.3
0.150	90	25	76.50	0.199	0.187	0.206	0.396	0.391	0.392	0.039	0.046	-17.7	0.034	0.042	-23.7	0.044	0.049	-10.8
0.150	120	10	102.00	0.681	0.653	0.728	0.442	0.437	0.439	0.034	0.035	-3.8	0.030	0.034	-13.4	0.042	0.037	11.3
0.150	120	15	102.00	0.456	0.437	0.462	0.432	0.426	0.428	0.036	0.043	-18.6	0.033	0.041	-25.3	0.038	0.046	-19.3
0.150	120	20	102.00	0.356	0.351	0.367	0.421	0.414	0.417	0.043	0.051	-18.9	0.042	0.048	-12.4	0.047	0.054	-15.2
0.150	120	25	102.00	0.305	0.293	0.319	0.411	0.403	0.406	0.053	0.059	-10.8	0.049	0.054	-9.8	0.060	0.063	-5.3
0.150	150	10	127.50	0.914	0.897	0.941	0.457	0.449	0.454	0.040	0.042	-5.7	0.039	0.042	-8.6	0.044	0.045	-3.4
0.150	150	15	127.50	0.626	0.624	0.644	0.446	0.438	0.443	0.045	0.052	-15.3	0.046	0.050	-9.7	0.049	0.056	-13.8
0.150	150	20	127.50	0.497	0.475	0.508	0.436	0.427	0.432	0.054	0.062	-13.9	0.050	0.059	-17.9	0.058	0.066	-15.2
0.150	150	25	127.50	0.448	0.438	0.476	0.425	0.416	0.421	0.072	0.071	1.6	0.071	0.067	5.5	0.082	0.077	6.8
0.325	60	10	40.50	0.609	0.598	0.621	0.413	0.412	0.410	0.053	0.051	4.3	0.050	0.047	6.0	0.060	0.052	13.8
0.325	60	15	40.50	0.405	0.394	0.400	0.403	0.400	0.399	0.058	0.055	5.0	0.052	0.050	4.1	0.056	0.056	1.1
0.325	60	20	40.50	0.299	0.298	0.305	0.392	0.389	0.388	0.059	0.059	0.2	0.060	0.053	10.6	0.066	0.060	8.9
0.325	60	25	40.50	0.246	0.243	0.241	0.382	0.378	0.377	0.071	0.063	11.7	0.070	0.057	18.9	0.068	0.064	5.6
0.325	90	10	60.75	0.978	0.971	0.936	0.428	0.424	0.425	0.064	0.061	5.1	0.064	0.059	7.1	0.054	0.064	-17.7
0.325	90	15	60.75	0.642	0.659	0.658	0.417	0.413	0.414	0.065	0.067	-2.6	0.074	0.064	13.3	0.073	0.070	4.8
0.325	90	20	60.75	0.485	0.475	0.484	0.407	0.402	0.403	0.072	0.073	-0.7	0.069	0.069	-0.5	0.073	0.076	-3.8
0.325	90	25	60.75	0.398	0.382	0.404	0.396	0.391	0.392	0.084	0.078	6.7	0.076	0.074	2.0	0.090	0.083	8.6
0.325	120	10	81.00	1.36	1.422	1.378	0.442	0.437	0.439	0.069	0.071	-2.9	0.084	0.072	14.4	0.074	0.076	-2.2
0.325	120	15	81.00	0.954	0.953	0.952	0.432	0.426	0.428	0.089	0.079	11.2	0.091	0.079	13.7	0.090	0.084	6.2
0.325	120	20	81.00	0.726	0.682	0.703	0.421	0.414	0.417	0.098	0.086	11.8	0.083	0.085	-2.8	0.090	0.093	-2.3
0.325	120	25	81.00	0.591	0.573	0.571	0.411	0.403	0.406	0.108	0.094	13.1	0.103	0.092	10.4	0.100	0.101	-0.8
0.325	150	10	101.25	1.948	1.874	1.86	0.457	0.449	0.454	0.103	0.081	21.6	0.094	0.085	9.9	0.090	0.088	2.4
0.325	150	15	101.25	1.355	1.243	1.243	0.446	0.438	0.443	0.122	0.091	25.8	0.098	0.093	5.0	0.096	0.098	-2.5
0.325	150	20	101.25	1.026	0.929	0.982	0.436	0.427	0.432	0.130	0.100	23.1	0.102	0.101	0.9	0.118	0.109	7.6
0.325	150	25	101.25	0.810	0.768	0.756	0.425	0.416	0.421	0.131	0.110	16.0	0.118	0.110	7.1	0.111	0.119	-7.8

(Continued...)

D-4 ...continued...

Feed Composition (F_C)	Feed Rate (F_T)	Trommel Speed (N)	Feed Rate of Undersize Berries (F_U)	Actual Mixture Hold-up (H_{ma}); (kg) Aperture Diameter, mm 4.00	4.25	4.75	Predicted Correction Factor (C_o) [from Table D-3] Aperture Diameter, mm 4.00	4.25	4.75	Correction Factor (C_u) Aperture Diameter, 4.00 mm Observed	Predicted	Deviation	Aperture Diameter, 4.25 mm Observed	Predicted	Deviation	Aperture Diameter, 4.75 mm Observed	Predicted	Deviation
(-)	kg/h	r/min	kg/h	kg	kg	kg	(-)	(-)	(-)	(-)	(-)	(%)	(-)	(-)	(%)	(-)	(-)	(%)
0.500	60	10	30.00	0.836	0.836	0.824	0.413	0.412	0.410	0.054	0.051	5.6	0.056	0.049	12.3	0.051	0.054	-6.6
0.500	60	15	30.00	0.544	0.548	0.551	0.403	0.400	0.399	0.054	0.055	-2.8	0.060	0.053	11.7	0.063	0.058	7.6
0.500	60	20	30.00	0.406	0.403	0.402	0.392	0.389	0.388	0.062	0.059	4.7	0.062	0.056	9.6	0.061	0.062	-1.7
0.500	60	25	30.00	0.314	0.319	0.317	0.382	0.378	0.377	0.057	0.063	-9.7	0.068	0.059	13.3	0.066	0.067	-1.1
0.500	90	10	45.00	1.293	1.294	1.334	0.428	0.424	0.425	0.054	0.064	-18.4	0.058	0.067	-14.7	0.073	0.070	3.4
0.500	90	15	45.00	0.878	0.857	0.876	0.417	0.413	0.414	0.074	0.070	4.9	0.067	0.072	-8.3	0.076	0.077	-0.5
0.500	90	20	45.00	0.649	0.647	0.658	0.407	0.402	0.403	0.077	0.076	1.6	0.081	0.077	4.8	0.088	0.083	5.7
0.500	90	25	45.00	0.506	0.511	0.509	0.396	0.391	0.392	0.076	0.082	-8.4	0.086	0.082	4.6	0.083	0.089	-7.9
0.500	120	10	60.00	1.895	1.836	1.877	0.442	0.437	0.439	0.088	0.078	11.6	0.077	0.085	-10.5	0.086	0.087	-0.9
0.500	120	15	60.00	1.224	1.228	1.243	0.432	0.426	0.428	0.082	0.085	-4.3	0.090	0.092	-2.0	0.093	0.095	-1.9
0.500	120	20	60.00	0.909	0.908	0.934	0.421	0.414	0.417	0.087	0.093	-6.7	0.094	0.098	-4.8	0.105	0.104	1.7
0.500	120	25	60.00	0.724	0.729	0.753	0.411	0.403	0.406	0.096	0.101	-5.6	0.107	0.105	1.8	0.120	0.112	7.0
0.500	150	10	75.00	2.48	2.459	2.499	0.457	0.449	0.454	0.098	0.091	7.6	0.101	0.103	-1.8	0.106	0.103	2.5
0.500	150	15	75.00	1.652	1.647	1.687	0.446	0.438	0.443	0.108	0.101	7.2	0.115	0.111	3.2	0.124	0.114	8.2
0.500	150	20	75.00	1.210	1.226	1.266	0.436	0.427	0.432	0.106	0.110	-4.1	0.122	0.119	2.0	0.135	0.124	8.1
0.500	150	25	75.00	0.994	0.981	1.029	0.425	0.416	0.421	0.131	0.120	8.4	0.133	0.128	4.2	0.155	0.135	13.2
0.675	60	10	19.50	1.025	1.024	1.023	0.413	0.412	0.410	0.024	0.023	3.7	0.027	0.027	-0.3	0.028	0.029	-3.2
0.675	60	15	19.50	0.669	0.667	0.669	0.403	0.400	0.399	0.027	0.027	1.4	0.030	0.030	-1.2	0.034	0.033	2.5
0.675	60	20	19.50	0.492	0.487	0.487	0.392	0.389	0.388	0.032	0.030	5.0	0.030	0.033	-10.6	0.032	0.038	-19.0
0.675	60	25	19.50	0.383	0.383	0.386	0.382	0.378	0.377	0.031	0.034	-10.2	0.039	0.037	6.6	0.047	0.042	10.3
0.675	90	10	29.25	1.613	1.606	1.644	0.428	0.424	0.425	0.037	0.039	-5.9	0.041	0.050	-22.2	0.061	0.050	18.7
0.675	90	15	29.25	1.067	1.067	1.069	0.417	0.413	0.414	0.052	0.045	13.0	0.061	0.055	10.1	0.061	0.056	7.6
0.675	90	20	29.25	0.783	0.776	0.799	0.407	0.402	0.403	0.054	0.051	5.5	0.056	0.060	-6.0	0.080	0.062	22.3
0.675	90	25	29.25	0.610	0.609	0.608	0.396	0.391	0.392	0.052	0.057	-8.6	0.063	0.065	-3.2	0.058	0.069	-17.9
0.675	120	10	39.00	2.254	2.266	2.265	0.442	0.437	0.439	0.052	0.056	-7.9	0.068	0.073	-6.6	0.063	0.070	-12.3
0.675	120	15	39.00	1.477	1.488	1.496	0.432	0.426	0.428	0.057	0.063	-11.5	0.077	0.079	-3.2	0.076	0.079	-3.1
0.675	120	20	39.00	1.093	1.089	1.093	0.421	0.414	0.417	0.066	0.071	-7.7	0.077	0.086	-11.8	0.074	0.087	-17.5
0.675	120	25	39.00	0.868	0.873	0.868	0.411	0.403	0.406	0.081	0.079	2.6	0.102	0.092	9.4	0.090	0.096	-6.1
0.675	150	10	48.75	3.018	3.044	3.007	0.457	0.449	0.454	0.091	0.072	20.5	0.115	0.096	16.7	0.093	0.091	2.5
0.675	150	15	48.75	1.994	1.935	1.964	0.446	0.438	0.443	0.103	0.082	20.8	0.089	0.104	-16.2	0.095	0.101	-6.8
0.675	150	20	48.75	1.467	1.472	1.469	0.436	0.427	0.432	0.106	0.092	13.3	0.127	0.112	11.7	0.115	0.112	2.6
0.675	150	25	48.75	1.163	1.156	1.161	0.425	0.416	0.421	0.118	0.101	14.4	0.132	0.120	8.5	0.126	0.122	2.4

End

Table E-1 Values of screening inaccuracy predicted by the semi-empirical and empirical models, and their percentage deviation from observed values

Feed Composition (F_C)	Feed Rate (F_T)	Trommel Speed (N)	Screening Inaccuracy, %									Deviation from Observed Value, %					
			Observed (S_i) [From Table G-1]			Predicted						Semi-Empirical Model 100(Si - Sise)/Si			Empirical Model 100(Si - Sie)/Si		
						Semi-Empirical Model (S_{ise}) [From Table D-2]			Empirical Model (S_{ie})								
			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm		
			4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75
(-)	kg/h	r/min	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0.150	60	10	26.3	37.7	29.7	33.1	32.0	33.4	31.2	30.0	31.3	-25.9	15.1	-12.5	-18.6	-14.1	-19.0
0.150	60	15	33.2	35.7	36.7	34.1	33.6	34.3	33.3	31.7	32.7	-2.7	5.9	6.5	-0.3	4.5	1.5
0.150	60	20	37.7	40.1	36.1	36.9	34.6	35.3	35.3	33.5	34.1	2.1	13.7	2.2	6.3	11.1	9.5
0.150	60	25	32.1	39.7	33.8	39.2	35.4	37.9	37.4	35.2	35.5	-22.2	10.9	-12.1	-16.5	-9.7	-10.6
0.150	90	10	32.9	39.0	30.1	32.6	31.6	35.1	34.2	32.8	34.5	0.9	19.1	-16.6	-3.9	0.3	-4.8
0.150	90	15	38.2	31.5	37.7	34.6	32.4	37.0	36.3	34.5	35.9	9.4	-2.9	1.9	5.0	9.7	6.0
0.150	90	20	34.2	33.9	38.1	35.7	33.0	38.0	38.3	36.2	37.3	-4.4	2.6	0.2	-12.0	-5.8	-9.0
0.150	90	25	43.6	33.4	36.5	37.7	34.4	39.9	40.4	38.0	38.7	13.5	-2.8	-9.3	7.3	12.8	11.2
0.150	120	10	33.9	36.4	37.1	31.9	30.9	34.9	37.3	35.6	37.7	5.9	15.1	5.9	-10.1	-5.0	-11.2
0.150	120	15	33.6	34.6	43.7	32.4	31.5	36.5	39.3	37.3	39.1	3.6	9.0	16.5	-16.9	-11.0	-16.3
0.150	120	20	43.4	41.6	41.5	33.6	33.4	39.9	41.4	39.0	40.5	22.6	19.7	3.9	4.6	10.1	6.7
0.150	120	25	40.2	48.7	49.6	36.1	39.3	44.5	43.4	40.7	41.9	10.2	19.4	10.3	-8.0	-1.2	-4.2
0.150	150	10	34.2	36.6	35.2	29.4	29.7	34.1	40.3	38.3	41.0	14.1	18.9	3.1	-17.8	-12.0	-19.9
0.150	150	15	43.1	34.7	43.8	31.6	32.0	36.2	42.3	40.1	42.4	26.7	7.9	17.4	1.8	6.9	1.6
0.150	150	20	49.3	42.5	41.6	36.9	35.0	38.3	44.4	41.8	43.8	25.1	17.7	7.9	9.9	15.2	11.1
0.150	150	25	56.8	55.0	45.9	42.3	40.1	44.9	46.4	43.5	45.2	25.5	27.1	2.2	18.3	23.4	20.4
0.325	60	10	17.2	18.3	18.4	17.5	19.3	22.3	20.5	20.5	21.4	-1.6	-5.5	-21.1	-19.0	-19.0	-24.3
0.325	60	15	24.9	19.2	25.8	19.7	20.8	22.7	22.6	22.2	22.8	20.9	-8.1	12.0	9.3	10.9	8.5
0.325	60	20	25.4	24.9	23.3	23.5	24.8	22.7	24.6	23.9	24.2	7.5	0.5	2.6	3.2	5.9	4.7
0.325	60	25	21.5	26.6	25.6	28.5	25.8	25.3	26.6	25.6	25.6	-32.6	3.1	1.2	-23.7	-19.1	-19.1
0.325	90	10	21.8	22.7	21.2	24.2	26.1	22.6	23.5	23.2	24.6	-11.0	-15.0	-6.6	-7.8	-6.4	-12.8
0.325	90	15	26.6	25.9	24.4	25.9	26.9	24.8	25.6	24.9	26.0	2.7	-3.9	-1.6	3.8	6.4	2.3
0.325	90	20	25.8	27.1	26.9	28.4	28.1	29.0	27.6	26.7	27.4	-10.1	-3.8	-7.8	-7.0	-3.5	-6.2
0.325	90	25	32.1	27.1	30.4	32.9	30.7	30.5	29.7	28.4	28.8	-2.5	-13.2	-0.3	7.5	11.5	10.3
0.325	120	10	27.4	27.6	25.6	26.3	27.6	25.9	26.5	26.0	27.8	4.0	0.1	-1.2	3.3	5.1	-1.4
0.325	120	15	28.3	31.4	29.4	28.6	28.9	27.6	28.6	27.7	29.2	-1.1	7.9	6.1	-1.1	2.1	-3.2
0.325	120	20	37.7	30.3	30.2	31.8	32.7	31.4	30.6	29.4	30.6	15.6	-8.0	-4.0	18.8	22.0	18.8
0.325	120	25	34.6	33.2	33.3	36.1	35.2	33.3	32.7	31.2	32.0	-4.3	-5.9	0.0	5.5	9.8	7.5
0.325	150	10	27.3	28.9	30.7	30.4	30.4	28.9	29.6	28.8	31.1	-11.4	-5.1	5.9	-8.4	-5.5	-13.9
0.325	150	15	35.5	31.3	30.3	32.7	31.8	30.0	31.6	30.5	32.5	10.4	-1.6	1.0	13.4	16.4	11.0
0.325	150	20	33.5	33.5	36.7	35.5	33.8	33.8	33.6	32.2	33.9	-6.0	-0.8	7.9	-0.3	3.9	-1.2
0.325	150	25	35.9	34.3	39.8	40.0	36.4	39.3	35.7	33.9	35.2	-8.4	-6.3	1.3	3.3	8.1	4.6

continued

E-1 ...continued

Feed Composition (F_C)	Feed Rate (F_T)	Trommel Speed (N)	Screening Inaccuracy, %									Deviation from Observed Value, %					
			Observed (S) [From Table G-1]			Predicted						Semi-Empirical Model 100(Si - Sise)/Si			Empirical Model 100(Si - Sie)/Si		
						Semi-Empirical Model (S_{se}) [From Table D-2]			Empirical Model (S_e)								
			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm			Aperture Diameter, mm		
			4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75	4.00	4.25	4.75
(-)	kg/h	r/min	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0.500	60	10	8.2	12.2	8.8	9.3	9.1	11.2	9.8	10.9	11.5	-13.4	25.4	-27.3	-19.5	-32.9	-40.3
0.500	60	15	9.9	13.4	11.3	10.0	9.4	12.0	11.8	12.6	12.9	-1.0	30.1	-6.2	-19.2	-27.3	-30.3
0.500	60	20	15.2	11.6	13.3	10.8	9.6	13.8	13.9	14.3	14.3	28.9	17.1	-3.7	8.6	5.9	5.9
0.500	60	25	12.7	14.9	16.7	12.5	10.7	15.9	15.9	16.1	15.7	1.6	28.0	4.8	-25.2	-26.8	-23.6
0.500	90	10	11.6	18.3	17.4	11.0	11.7	13.4	12.8	13.7	14.7	5.2	36.1	23.0	-10.3	-18.1	-26.7
0.500	90	15	10.5	15.7	14.7	12.2	11.9	14.1	14.9	15.4	16.1	-16.2	24.4	4.1	-41.9	-46.7	-53.4
0.500	90	20	11.1	13.1	18.9	13.6	15.5	16.3	16.9	17.1	17.5	-22.2	-18.7	13.8	-51.9	-53.7	-57.3
0.500	90	25	13.6	19.5	24.2	15.3	17.9	18.8	18.9	18.8	18.9	-12.4	8.1	22.3	-38.9	-38.2	-38.9
0.500	120	10	12.3	11.7	24.8	13.1	15.7	16.9	15.8	16.4	17.9	-6.5	-34.7	31.8	-28.4	-33.3	-45.5
0.500	120	15	14.8	16.0	20.1	14.3	17.0	18.3	17.9	18.1	19.3	3.4	-6.0	9.0	-21.0	-22.3	-30.4
0.500	120	20	14.9	20.3	19.6	16.2	18.9	20.1	19.9	19.9	20.7	-8.7	6.7	-2.5	-33.5	-33.5	-38.9
0.500	120	25	21.5	21.4	27.3	20.0	23.0	24.1	22.0	21.6	22.1	7.0	-7.5	11.7	-2.3	-0.5	-2.8
0.500	150	10	13.2	16.7	23.5	16.0	16.1	17.4	18.8	19.2	21.2	-21.2	3.6	26.1	-42.4	-45.5	-60.6
0.500	150	15	17.7	17.2	23.0	17.8	18.3	19.5	20.9	20.9	22.5	-0.5	-6.6	15.2	-18.1	-18.1	-27.1
0.500	150	20	18.9	23.0	21.6	20.0	20.3	21.3	22.9	22.6	23.9	-5.8	11.6	1.4	-21.1	-19.6	-26.4
0.500	150	25	27.9	24.7	26.9	23.2	24.0	27.1	25.0	24.4	25.3	16.7	2.9	-0.7	10.3	12.4	9.2
0.675	60	10	4.1	3.9	4.4	4.0	4.2	4.1	-0.9	1.3	1.6	2.5	-6.5	6.9	121.9	68.3	61.0
0.675	60	15	4.3	4.2	3.6	4.2	4.3	4.1	1.1	3.0	3.0	2.4	-2.9	-13.8	74.4	30.3	30.3
0.675	60	20	4.1	5.7	4.7	4.7	4.7	4.4	3.2	4.8	4.4	-14.7	18.2	6.3	21.9	-17.2	-7.4
0.675	60	25	5.9	8.0	5.7	5.4	6.5	5.1	5.2	6.5	5.8	8.5	18.4	10.6	11.9	-10.1	1.7
0.675	90	10	4.8	4.4	4.5	4.2	4.3	4.3	2.1	4.1	4.8	12.5	3.0	4.5	56.3	14.6	0.0
0.675	90	15	4.3	4.4	4.2	4.4	4.5	4.5	4.1	5.8	6.2	-2.3	-2.7	-7.2	4.7	-34.8	-44.1
0.675	90	20	7.9	6.9	6.6	5.0	5.5	6.5	6.2	7.5	7.6	36.7	20.7	1.5	21.5	5.1	3.8
0.675	90	25	10.4	8.0	7.8	7.3	7.0	8.2	8.2	9.3	9.0	29.8	13.0	-5.2	21.2	10.6	13.5
0.675	120	10	5.3	8.5	8.4	5.9	7.4	7.3	5.1	6.9	8.0	-11.4	13.3	13.1	3.7	-30.2	-51.0
0.675	120	15	6.6	8.4	9.8	6.6	7.8	7.9	7.1	8.6	9.4	0.0	7.6	19.4	-7.6	-30.3	-42.5
0.675	120	20	7.9	9.9	12.3	7.3	8.7	9.2	9.2	10.3	10.8	7.6	12.3	25.2	-16.4	-30.4	-36.7
0.675	120	25	11.4	11.7	11.7	8.5	10.7	10.8	11.2	12.0	12.2	25.4	8.4	7.7	1.7	-5.3	-7.0
0.675	150	10	12.6	9.3	11.3	7.0	8.9	8.7	8.1	9.6	11.2	44.5	4.3	23.3	35.7	23.8	11.1
0.675	150	15	13.5	11.4	12.4	7.8	10.2	9.5	10.2	11.3	12.6	42.2	10.7	23.4	24.4	16.3	6.6
0.675	150	20	9.4	14.5	13.7	8.8	12.4	11.1	12.2	13.1	14.0	6.4	14.7	19.0	-29.8	-39.4	-49.0
0.675	150	25	10.6	15.4	14.3	11.0	14.5	13.1	14.2	14.8	15.4	-3.8	5.7	8.4	-34.0	-39.6	-45.3

End

Table F-1 Screening inaccuracies of the trommel of 4.00-mm apertures at different feed compositions, feed rates and trommel speeds

Feed Rate kg/h	Replication No.	Screening Inaccuracy, %															
		Feed Composition, (-)															
		0.150				0.325				0.500				0.675			
		Trommel Speed, r/min															
		10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	R1	29.0	28.4	34.3	33.2	20.3	20.8	25.6	26.4	10.7	10.5	12.6	12.8	4.3	4.1	4.5	6.9
60	R2	30.9	33.0	34.6	38.8	20.6	18.1	23.9	25.9	8.7	10.9	14.1	15.2	4.2	4.2	5.4	6.4
60	R3	34.2	30.9	37.4	35.7	21.7	22.3	22.1	22.5	8.3	12.4	12.4	12.7	4.4	4.6	5.2	6.8
60	R4	28.4	35.1	32.6	36.7	18.1	19.6	24.5	26.2	9.5	11.4	11.7	16.3	4.6	4.3	4.7	5.5
60	R5	30.4	31.3	36.2	37.3	21.3	22.8	21.3	28.2	7.9	8.9	10.8	15.9	4.8	4.7	4.2	7.5
60	R6	32.6	32.1	30.8	36.6	22.6	24.1	19.9	24.7	9.3	11.1	11.3	14.6	5.0	4.9	4.4	6.5
	Mean	30.9	31.8	34.3	36.4	20.8	21.3	22.9	25.7	9.1	10.9	12.2	14.6	4.6	4.5	4.7	6.6
90	R1	35.7	35.7	36.2	38.5	25.4	28.3	27.5	28.2	12.1	12.1	14.4	12.9	3.5	4.6	6.3	9.2
90	R2	36.1	38.6	39.5	40.2	27.7	26.1	26.5	34.5	12.7	12.1	12.5	17.6	4.4	4.5	6.5	8.6
90	R3	32.8	36.5	35.9	46.4	23.6	29.8	31.7	33.6	14.9	13.1	14.5	16.9	4.2	4.7	6.8	8.2
90	R4	34.3	32.8	43.2	41.9	25.2	25.3	28.4	30.2	13.1	12.4	13.6	17.9	3.6	4.8	5.8	9.0
90	R5	37.2	35.3	38.9	42.8	22.1	26.4	30.5	29.9	10.9	15.2	16.3	13.9	4.0	4.9	5.4	8.1
90	R6	34.6	35.5	36.4	39.4	23.3	28.4	32.1	30.2	11.8	12.2	14.1	18.4	4.1	5.2	5.7	8.7
	Mean	35.1	35.7	38.4	41.5	24.6	27.4	29.5	31.1	12.6	12.9	14.2	16.3	4.0	4.8	6.1	8.6
120	R1	35.3	40.2	37.6	40.9	32.6	34.8	35.5	31.9	13.2	15.8	17.2	21.3	5.3	5.5	7.4	9.8
120	R2	35.6	36.8	40.5	42.6	31.1	29.6	37.4	37.6	15.6	15.6	15.7	20.9	6.1	6.5	8.0	8.9
120	R3	38.2	39.4	38.2	39.7	30.1	36.1	35.4	32.1	13.4	18.1	16.5	21.4	5.8	7.0	7.1	10.1
120	R4	32.8	37.2	39.4	43.6	26.8	30.2	32.1	36.5	12.7	14.5	17.9	23.4	6.0	6.1	7.9	10.7
120	R5	34.3	34.7	37.1	44.9	27.2	30.0	31.5	38.8	14.6	13.9	20.2	19.6	6.9	5.9	8.1	9.7
120	R6	36.1	38.4	42.3	38.3	28.2	33.3	31.3	33.7	13.9	15.6	18.1	18.4	6.2	7.1	6.8	9.6
	Mean	35.4	37.8	39.2	41.7	29.3	32.3	33.9	35.1	13.9	15.6	17.6	20.8	6.1	6.4	7.6	9.8
150	R1	36.8	36.2	48.3	48.6	29.2	36.4	35.8	42.8	18.6	16.1	20.4	24.8	8.4	8.8	11.6	13.5
150	R2	36.8	37.2	47.6	49.1	30.4	33.2	36.1	36.6	16.5	20.4	22.6	23.1	9.1	8.5	10.2	14.5
150	R3	41.4	36.2	42.5	54.3	31.1	33.1	38.8	39.3	17.6	17.3	19.8	27.6	8.3	8.2	11.5	13.7
150	R4	35.4	42.6	46.7	56.7	35.3	37.6	40.7	38.2	14.2	16.8	18.1	24.2	7.9	9.0	10.4	13.4
150	R5	38.2	35.9	44.8	53.2	29.8	32.6	37.4	40.6	17.1	21.1	23.3	25.1	8.2	9.2	10.6	13.2
150	R6	37.1	40.3	43.9	51.5	31.6	39.5	34.8	38.7	15.2	19.2	20.5	23.6	7.3	9.9	11.2	12.6
	Mean	37.6	38.1	45.6	52.2	31.2	35.4	37.3	39.4	16.5	18.5	20.8	24.7	8.2	8.9	10.9	13.5

Table F-2 Screening inaccuracies of the trommel of 4.25-mm apertures at different feed compositions, feed rates and trommel speeds

Feed Rate kg/h	Replication No.	Screening Inaccuracy, % Feed Composition, (-) 0.150 Trommel Speed, r/min 10	15	20	25	0.325 10	15	20	25	0.500 10	15	20	25	0.675 10	15	20	25
60	R1	35.7	31.2	36.1	36.6	18.7	20.3	21.8	25.2	10.9	8.8	13.4	12.0	4.4	4.3	5.4	8.0
60	R2	32.8	34.3	37.9	37.8	18.2	22.3	20.7	27.4	10.5	10.9	12.1	14.1	4.5	4.2	6.2	7.5
60	R3	30.3	33.5	35.1	34.2	19.3	19.3	22.8	25.3	9.3	11.2	11.9	10.9	4.9	4.4	5.1	8.1
60	R4	33.2	35.2	35.9	36.0	20.8	17.7	25.0	25.5	12.1	9.6	10.2	13.4	4.6	5.0	5.0	8.8
60	R5	32.5	33.8	33.8	36.7	21.7	21.2	23.1	21.8	11.3	12.1	12.3	13.2	5.1	4.8	5.4	8.2
60	R6	32.0	32.8	36.6	39.5	17.8	19.9	19.8	24.7	11.5	11.0	11.6	14.7	5.0	4.6	4.9	6.7
	Mean	32.8	33.5	35.9	36.8	19.4	20.1	22.2	25.0	10.9	10.6	11.9	13.1	4.8	4.6	5.3	7.9
90	R1	33.3	31.2	33.9	37.5	24.4	25.4	24.8	27.1	16.3	15.3	15.6	16.8	5.1	4.2	6.1	8.4
90	R2	33.6	33.3	36.7	39.4	22.8	24.7	27.8	26.6	14.9	14.2	16.5	21.7	4.6	4.9	5.1	9.6
90	R3	35.4	35.2	33.5	37.1	25.6	24.2	23.3	29.7	15.6	13.3	14.1	20.8	5.0	4.3	6.2	7.8
90	R4	30.2	33.4	34.8	38.3	23.9	22.7	26.7	27.9	14.7	17.1	16.9	17.3	4.2	5.1	6.3	7.9
90	R5	34.2	35.1	33.7	33.6	21.0	24.2	25.4	24.6	13.4	16.2	17.5	17.2	5.2	4.7	6.4	9.0
90	R6	32.6	35.3	31.8	39.3	22.1	26.8	25.8	28.8	13.7	15.4	18.7	16.7	4.8	4.8	7.7	9.5
	Mean	33.2	33.9	34.1	37.5	23.3	24.7	25.6	27.5	14.8	15.3	16.6	18.4	4.8	4.7	6.3	8.7
120	R1	33.8	34.1	41.3	43.7	26.7	28.2	28.7	30.7	15.9	18.7	16.3	21.7	8.6	11.1	10.4	11.7
120	R2	33.5	36.8	45.2	47.4	26.5	27.3	29.6	32.1	17.9	16.1	22.2	24.1	10.3	8.9	9.1	11.9
120	R3	32.1	41.1	41.0	43.4	27.9	31.7	32.8	28.1	16.1	17.9	20.3	22.4	10.1	7.7	10.8	13.5
120	R4	34.6	34.8	38.3	39.6	29.3	27.9	28.2	31.2	13.8	16.4	18.8	20.6	9.2	8.2	12.1	12.2
120	R5	35.3	36.1	42.5	43.9	26.2	25.9	26.1	34.4	14.9	15.7	17.7	18.8	7.4	10.6	11.8	14.1
120	R6	37.4	37.3	42.9	44.3	23.2	28.5	30.5	29.9	15.9	14.8	18.2	22.1	7.5	9.1	9.5	12.3
	Mean	34.5	36.7	41.9	43.7	26.6	28.3	29.3	31.1	15.8	16.6	18.9	21.6	8.9	9.3	10.6	12.6
150	R1	35.5	31.8	39.7	54.9	33.2	31.0	31.6	29.7	18.7	23.7	21.1	26.8	10.5	11.3	15.0	16.1
150	R2	34.7	37.4	38.7	48.3	29.3	35.3	33.3	33.1	22.1	21.2	24.6	23.9	12.1	10.7	14.6	13.9
150	R3	30.6	40.1	46.6	49.9	30.8	33.0	31.1	34.8	20.4	16.8	18.2	22.1	10.2	11.9	13.5	13.6
150	R4	32.4	35.4	41.2	46.7	32.1	31.7	34.7	32.4	17.7	18.2	25.4	20.3	9.3	10.9	12.2	16.4
150	R5	33.1	36.2	42.5	45.7	26.8	32.2	29.1	36.6	17.5	18.7	21.5	24.6	9.9	12.2	12.1	15.1
150	R6	36.6	36.9	39.1	51.6	30.1	29.2	32.9	34.2	16.8	17.7	20.7	22.6	10.8	13.7	13.4	15.2
	Mean	33.8	36.3	41.3	49.5	30.4	32.1	32.1	33.5	18.9	19.4	21.9	23.4	10.5	11.8	13.5	15.1

Table F-3 Screening inaccuracies of the trommel of 4.75-mm apertures at different feed compositions, feed rates and trommel speeds

Feed Rate kg/h	Replication No.	Screening Inaccuracy, %															
		Feed Composition, (-)															
		0.150				0.325				0.500				0.675			
		Trommel Speed, r/min															
		10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	R1	33.5	30.4	30.1	31.4	22.3	22.6	24.6	23.0	10.1	15.4	13.3	17.5	3.9	3.3	4.7	5.8
60	R2	35.8	33.3	34.1	34.4	18.7	20.3	26.1	23.9	11.2	12.8	12.1	13.4	3.7	3.2	4.9	6.3
60	R3	33.1	34.3	33.5	34.9	21.8	23.7	24.8	23.7	11.6	13.9	16.2	14.6	3.4	4.1	5.3	6.7
60	R4	32.3	34.4	36.9	34.5	23.7	21.9	21.1	21.3	12.5	12.4	15.6	15.8	4.6	4.1	5.9	7.2
60	R5	32.6	33.9	34.4	35.2	21.1	25.1	19.8	26.4	10.3	11.7	14.3	16.9	3.1	4.2	5.1	6.0
60	R6	29.3	36.8	33.1	38.6	20.6	20.2	21.1	24.5	9.3	14.6	13.3	15.1	4.5	3.8	5.5	5.4
	Mean	32.8	33.9	33.7	34.8	21.4	22.3	22.9	23.8	10.8	13.5	14.1	15.6	3.9	3.8	5.2	6.2
90	R1	33.1	35.7	31.9	40.4	25.1	25.3	23.6	27.3	17.3	18.9	18.4	19.7	3.6	4.3	6.7	9.5
90	R2	33.9	37.7	36.8	33.2	24.3	27.9	25.6	25.1	16.6	15.2	18.2	21.5	4.7	4.5	7.3	9.6
90	R3	29.3	35.6	38.3	37.1	22.4	24.6	27.2	27.6	17.0	17.3	19.1	19.6	4.6	5.1	6.9	7.9
90	R4	33.6	34.7	35.9	37.6	27.8	25.3	29.8	28.7	18.1	16.8	18.9	21.1	4.7	5.2	7.1	7.9
90	R5	31.5	31.6	36.2	38.4	25.2	22.3	26.5	27.4	14.8	17.2	20.6	18.1	4.6	4.1	5.9	7.5
90	R6	36.4	33.9	33.1	35.8	25.8	24.7	26.8	31.6	16.5	19.6	16.5	20.9	4.9	5.0	7.4	7.2
	Mean	33.0	34.9	35.4	37.1	25.1	25.0	26.6	28.0	16.7	17.5	18.6	20.2	4.5	4.7	6.9	8.3
120	R1	34.5	37.9	40.0	48.6	26.8	29.3	29.7	30.2	21.1	20.4	23.8	24.1	7.2	8.7	10.5	12.1
120	R2	37.9	37.7	39.7	45.8	28.7	28.2	28.4	30.9	21.8	21.4	23.6	25.4	5.9	8.7	10.1	13.8
120	R3	37.6	38.7	37.6	44.7	25.9	27.3	27.4	29.6	22.6	23.1	22.6	23.5	6.4	9.4	9.3	12.7
120	R4	37.3	34.2	41.1	41.7	23.8	27.9	29.1	31.1	22.4	23.3	23.4	24.0	7.8	8.4	9.8	12.3
120	R5	41.1	38.2	43.9	45.3	27.6	25.7	30.7	28.5	20.7	22.5	20.2	22.1	7.5	7.9	11.1	13.2
120	R6	38.2	42.1	41.7	45.1	27.3	26.6	26.7	32.3	20.0	22.1	20.7	23.5	7.6	9.6	10.9	13.1
	Mean	37.8	38.1	40.7	45.2	26.7	27.5	28.7	30.4	21.4	22.1	22.4	23.8	7.1	8.8	10.3	12.9
150	R1	39.8	40.2	41.8	46.3	31.5	34.7	35.9	37.3	20.9	22.2	23.4	26.6	10.2	10.9	11.7	12.9
150	R2	37.5	44.3	44.7	48.2	29.5	33.4	33.8	36.1	20.1	24.4	24.3	24.7	10.1	10.4	12.1	13.0
150	R3	44.2	40.1	49.7	50.3	30.7	33.1	30.6	38.2	23.9	21.5	22.0	27.7	11.5	11.2	12.2	14.3
150	R4	36.9	41.4	47.2	50.6	31.2	30.9	33.2	33.9	22.6	22.5	21.9	25.7	11.7	11.9	11.1	12.6
150	R5	40.5	41.1	46.1	52.3	32.5	31.6	33.6	40.1	22.9	19.9	21.7	23.6	10.3	10.5	11.3	12.1
150	R6	37.2	37.8	44.3	53.3	34.6	29.9	33.2	37.8	21.1	23.4	26.3	23.9	9.8	11.5	12.8	13.8
	Mean	39.4	40.8	45.6	50.2	31.7	32.3	33.4	37.2	21.9	22.3	23.3	25.4	10.6	11.1	11.9	13.1

Table F-4 Weights of berries collected from different outlets, and the observed screening inaccuracies of the trommel of 4.00-mm apertures at different feed compositions, feed rates and trommel speeds

(*Mean of 6 replications*)

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Weight of Fines sifted through each Zone: First 15-cm Zone	Second 15-cm Zone	Third 15-cm Zone	Fourth 15-cm Zone	Fifth 15-cm Zone	Sixth 15-cm Zone	Weight of Berries Clogging Apertures	Weight of Tailings	Total Weight	Weight of Undersize Berries in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	g	g	g	g	g	g	g	g	%
120	0.150	60	10	544.6	348.3	316.7	181.6	109.6	69.3	0.4	437.8	2008.3	135.4	30.9
			15	504.9	403.1	336.3	176.9	84.6	57.3	0.5	445.0	2008.6	141.7	31.8
			20	516.6	350.8	326.7	180.6	104.9	53.5	0.3	452.5	1985.9	155.3	34.3
			25	538.1	323.7	321.8	164.7	111.3	67.6	0.6	474.4	2002.2	172.9	36.4
80		90	10	531.9	363.5	292.4	186.7	96.8	65.4	0.6	471.4	2008.7	165.7	35.1
			15	501.3	370.5	313.2	181.3	98.1	66.8	0.7	477.7	2009.6	170.8	35.7
			20	525.3	325.6	281.3	216.3	112.3	56.9	0.7	478.7	1997.1	184.1	38.4
			25	531.0	306.4	256.3	201.3	117.9	62.8	0.6	512.6	1988.9	213.0	41.5
60		120	10	521.2	296.8	280.9	204.3	143.6	89.7	0.7	468.6	2005.8	166.1	35.4
			15	509.2	313.2	267.1	200.7	141.7	83.5	0.6	483.6	1999.6	183.0	37.8
			20	482.6	321.4	254.9	215.6	140.2	87.8	0.6	503.8	2006.9	197.7	39.2
			25	445.6	336.1	243.2	228.2	139.1	96.3	0.7	518.7	2007.9	216.6	41.7
48		150	10	475.2	322.3	254.1	234.7	139.9	95.2	0.5	478.5	2000.4	180.1	37.6
			15	414.7	339.2	246.1	256.2	148.3	109.4	0.6	489.2	2003.7	186.6	38.1
			20	407.8	319.9	229.8	238.9	141.2	106.2	0.6	561.0	2005.4	256.1	45.6
			25	368.4	263.5	216.2	248.9	155.6	121.2	0.5	627.5	2001.8	327.8	52.2
120	0.325	60	10	565.7	345.8	168.9	63.4	29.5	14.3	0.4	823.5	2011.5	171.4	20.8
			15	555.6	338.3	159.6	69.7	38.3	16.7	0.4	830.3	2008.9	176.9	21.3
			20	547.3	307.9	150.1	81.2	45.3	19.3	0.3	837.4	1988.8	191.8	22.9
			25	521.8	293.2	145.8	88.9	54.4	25.6	0.3	884.6	2014.6	227.4	25.7
80		90	10	506.1	285.4	183.3	98.1	48.2	16.7	0.4	871.4	2009.6	214.5	24.6
			15	483.5	284.3	184.7	88.3	46.7	19.1	0.3	886.9	1993.8	243.1	27.4
			20	499.6	264.7	158.1	84.4	50.2	20.3	0.5	912.1	1989.9	269.2	29.5
			25	488.3	257.1	152.9	78.6	52.9	22.4	0.5	949.9	2002.6	295.6	31.1
60		120	10	465.4	249.3	175.2	93.3	72.9	28.8	0.4	921.5	2006.8	270.1	29.3
			15	422.7	221.5	186.9	102.5	85.4	19.4	0.5	965.7	2004.6	312.1	32.3
			20	419.0	252.6	167.0	99.7	55.3	23.1	0.6	989.0	2006.3	335.5	33.9
			25	423.6	248.7	163.3	88.4	51.3	21.7	0.6	995.4	1993.0	349.6	35.1
48		150	10	407.5	262.3	189.1	83.3	74.1	34.2	0.7	954.4	2005.6	298.0	31.2
			15	382.6	253.6	174.4	95.6	64.1	20.9	0.7	1009.5	2001.4	357.6	35.4
			20	340.7	279.7	171.3	55.9	81.4	31.7	0.8	1034.3	1995.8	386.1	37.3
			25	349.1	271.2	153.5	65.8	54.6	35.6	0.6	1066.2	1996.6	420.3	39.4
120	0.500	60	10	523.2	224.1	91.5	38.1	21.2	13.9	0.6	1103.7	2016.3	100.5	9.1
			15	509.7	224.3	84.6	36.4	22.5	12.2	0.4	1124.5	2014.6	122.6	10.9
			20	475.1	219.2	81.1	39.6	22.4	16.3	0.4	1137.4	1991.5	138.8	12.2
			25	430.3	229.3	82.1	42.6	23.6	14.9	0.6	1166.0	1989.4	170.3	14.6
80		90	10	431.2	230.7	99.1	53.4	26.3	17.9	0.5	1151.9	2011.0	145.2	12.6
			15	413.6	236.2	95.6	59.7	32.7	17.4	0.4	1154.2	2009.8	148.9	12.9
			20	403.4	241.8	92.3	47.2	30.1	15.9	0.3	1161.4	1992.4	165.0	14.2
			25	391.4	236.1	84.7	43.9	29.7	16.7	0.5	1193.3	1996.3	194.6	16.3
60		120	10	386.6	240.3	96.4	53.2	32.9	24.4	0.4	1158.1	1992.3	161.0	13.9
			15	371.5	224.5	100.1	61.6	39.7	23.4	0.3	1186.8	2007.9	185.2	15.6
			20	341.7	211.8	112.2	68.8	31.7	22.3	0.4	1217.2	2006.1	214.3	17.6
			25	326.9	212.3	99.4	55.8	24.4	17.7	0.5	1267.3	2004.3	263.7	20.8
48		150	10	316.5	231.4	120.3	69.7	36.9	24.3	0.8	1194.8	1994.7	197.3	16.5
			15	308.2	236.8	112.1	46.7	35.4	36.2	0.7	1225.2	2001.3	226.8	18.5
			20	302.5	225.1	103.6	41.2	38.9	21.3	0.6	1265.2	1998.4	263.3	20.8
			25	276.1	201.3	99.7	43.6	35.1	15.6	0.6	1333.3	2005.3	329.5	24.7

continued

F-4 ... continued ..

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Weight of Fines sifted through each Zone: First 15-cm Zone	Second 15-cm Zone	Third 15-cm Zone	Fourth 15-cm Zone	Fifth 15-cm Zone	Sixth 15-cm Zone	Weight of Berries Clogging Apertures	Weight of Tailings	Total Weight	Weight of Undersize Berries in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	g	g	g	g	g	g	g	g	%
120	0.675	60	10	320.8	142.8	67.5	33.8	18.3	10.6	0.8	1418.9	2013.5	65.3	4.6
			15	365.9	130.3	52.6	23.3	15.5	8.2	0.6	1418.5	2014.9	63.9	4.5
			20	338.5	138.7	50.5	24.6	13.1	6.7	0.5	1413.7	1986.3	66.5	4.7
			25	316.9	137.7	61.5	24.7	14.3	8.2	0.7	1447.7	2011.7	95.6	6.6
80		90	10	283.9	143.4	85.9	47.2	21.7	11.6	0.6	1412.4	2006.7	56.5	4.0
			15	316.3	139.3	63.1	33.7	24.8	9.4	0.7	1417.8	2005.1	68.1	4.8
			20	325.3	133.4	47.4	27.3	15.1	8.7	0.6	1435.0	1992.8	87.6	6.1
			25	304.2	131.9	45.3	24.7	13.2	9.7	0.7	1475.9	2005.6	127.0	8.6
60		120	10	291.7	137.5	76.7	32.1	18.8	9.6	0.8	1439.1	2006.3	87.8	6.1
			15	279.1	124.8	80.1	37.1	20.4	11.3	0.7	1439.4	1992.9	92.2	6.4
			20	256.9	129.4	79.8	36.9	23.5	10.8	0.6	1470.2	2008.1	111.8	7.6
			25	263.6	122.9	58.2	31.6	18.4	6.8	0.8	1491.9	1994.2	146.3	9.8
48		150	10	264.4	122.4	68.6	37.8	23.4	13.3	0.9	1473.5	2004.3	120.9	8.2
			15	216.9	133.4	83.4	41.5	33.6	15.1	0.8	1480.0	2004.7	131.8	8.9
			20	233.8	119.7	73.8	28.5	20.6	12.7	0.6	1511.5	2001.2	164.8	10.9
			25	216.6	106.7	50.6	34.7	21.9	8.5	0.8	1565.8	2005.6	211.5	13.5

End

Table F-5 Weights of berries collected from different outlets, and the observed screening inaccuracies of the trommel of 4.25-mm apertures at different feed compositions, feed rates and trommel speeds

(Mean of 6 replications)

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Weight of Fines sifted through each Zone: First 15-cm Zone	Second 15-cm Zone	Third 15-cm Zone	Fourth 15-cm Zone	Fifth 15-cm Zone	Sixth 15-cm Zone	Weight of Berries Clogging Apertures	Weight of Tailings	Total Weight	Weight of Undersize Berries in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	g	g	g	g	g	g	g	g	%
120	0.150	60	10	555.1	401.5	316.7	150.2	71.2	48.3	0.8	444.6	1988.4	146.1	32.8
			15	531.8	346.6	309.1	176.2	106.9	76.2	0.5	438.3	1985.6	147.0	33.5
			20	544.7	396.9	313.7	146.3	75.6	49.7	0.7	456.7	1984.3	164.2	35.9
			25	576.3	363.6	311.4	145.4	76.3	53.6	0.6	486.0	2013.2	179.1	36.8
80		90	10	580.6	349.8	279.9	168.5	101.5	71.9	0.7	447.5	2000.4	148.8	33.2
			15	568.7	404.2	301.6	144.2	76.3	49.8	0.4	448.9	1994.1	152.3	33.9
			20	541.9	397.8	318.7	151.3	78.4	58.3	0.6	459.6	2006.6	156.9	34.1
			25	563.4	373.1	313.6	140.4	79.6	55.8	0.5	479.0	2005.4	179.8	37.5
60		120	10	552.7	333.1	320.1	158.7	116.8	61.3	0.5	460.0	2003.2	158.9	34.5
			15	586.7	308.1	251.6	173.2	126.7	76.2	0.6	481.4	2004.5	176.9	36.7
			20	544.7	281.9	282.4	175.6	134.6	61.3	0.5	514.6	1995.6	215.8	41.9
			25	469.8	397.6	285.7	152.7	111.6	52.4	0.7	527.9	1998.4	231.0	43.7
48		150	10	475.8	411.2	308.4	167.4	123.8	62.7	0.6	451.2	2001.1	152.7	33.8
			15	543.2	313.2	297.9	179.4	129.7	65.4	0.5	476.3	2005.6	173.1	36.3
			20	492.1	322.1	285.0	178.6	136.4	78.4	0.4	501.8	1994.8	207.4	41.3
			25	438.4	283.1	274.6	183.1	145.6	83.4	0.6	589.9	1998.7	292.3	49.5
120	0.325	60	10	511.1	347.2	157.5	89.2	57.8	25.3	0.5	801.1	1989.7	155.5	19.4
			15	545.7	345.7	161.6	71.6	39.2	17.7	0.7	812.2	1994.4	163.4	20.1
			20	521.4	336.9	158.6	82.9	48.3	21.1	0.6	839.9	2009.7	186.6	22.2
			25	481.4	307.3	168.7	99.2	56.2	26.6	0.4	875.5	2015.3	219.0	25.0
80		90	10	473.6	334.8	165.4	94.2	57.6	29.6	0.4	854.5	2010.1	199.2	23.3
			15	468.9	318.6	185.2	90.3	49.1	20.5	0.5	859.5	1992.6	212.4	24.7
			20	504.5	301.4	161.5	85.5	51.2	21.3	0.6	883.0	2009.0	226.2	25.6
			25	473.5	319.7	155.2	82.3	54.0	24.4	0.6	897.6	2007.3	247.0	27.5
60		120	10	362.6	317.2	202.1	135.1	66.5	31.2	0.6	891.2	2006.5	237.2	26.6
			15	358.9	269.5	211.3	137.9	74.1	39.5	0.6	903.6	1995.4	255.9	28.3
			20	372.5	314.3	196.3	106.7	64.6	30.3	0.8	909.2	1994.7	266.6	29.3
			25	419.5	305.6	168.4	91.6	55.4	21.6	0.7	930.8	1993.6	289.7	31.1
48		150	10	401.3	307.1	172.9	94.8	62.2	31.6	0.7	933.5	2004.1	284.0	30.4
			15	379.6	272.3	189.4	101.4	67.3	27.2	0.7	961.0	1998.9	308.7	32.1
			20	343.7	297.4	184.0	108.5	67.1	36.1	0.6	963.3	2000.7	309.4	32.1
			25	346.9	288.1	173.6	107.2	70.4	35.9	0.6	973.1	1995.8	326.2	33.5
120	0.500	60	10	440.2	241.9	116.2	54.5	30.3	13.6	0.3	1118.1	2015.1	121.9	10.9
			15	501.6	206.4	95.2	43.1	20.9	10.3	0.4	1120.4	1998.3	118.8	10.6
			20	496.7	205.1	78.9	42.9	23.6	14.1	0.6	1133.5	1995.4	135.0	11.9
			25	472.8	210.3	78.4	43.8	26.6	15.3	0.6	1150.5	1998.3	150.8	13.1
80		90	10	452.8	201.6	85.3	53.2	24.1	11.8	0.3	1180.5	2009.6	174.8	14.8
			15	431.9	198.7	89.2	46.5	30.2	20.8	0.3	1174.1	1991.7	179.7	15.3
			20	421.7	185.9	91.7	53.6	30.7	16.3	0.4	1195.0	1995.3	198.4	16.6
			25	425.6	175.8	87.9	46.1	26.9	14.4	0.3	1226.7	2003.7	225.8	18.4
60		120	10	372.8	203.9	136.5	62.2	28.4	12.9	0.7	1190.6	2008.0	188.2	15.8
			15	409.6	194.1	111.2	50.4	24.9	11.6	0.6	1205.9	2008.3	200.3	16.6
			20	384.3	165.4	108.4	55.6	30.6	21.1	0.7	1226.7	1992.8	232.0	18.9
			25	394.5	155.9	86.1	49.3	23.6	10.8	0.5	1273.4	1994.1	275.2	21.6
48		150	10	432.2	173.9	84.4	39.4	22.4	13.7	0.6	1239.1	2005.7	234.3	18.9
			15	396.9	198.6	86.4	36.6	19.7	12.3	0.4	1245.9	1996.8	241.8	19.4
			20	386.7	215.3	53.9	32.8	18.4	10.1	0.6	1284.4	2002.2	281.4	21.9
			25	374.3	165.3	77.5	43.1	24.5	11.3	0.5	1308.5	2005.0	306.3	23.4

continued ..

F-5 .. continued ..

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Weight of Fines sifted through each Zone: First 15-cm Zone	Second 15-cm Zone	Third 15-cm Zone	Fourth 15-cm Zone	Fifth 15-cm Zone	Sixth 15-cm Zone	Weight of Berries Clogging Apertures	Weight of Tailings	Total Weight	Weight of Undersize Berries in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	g	g	g	g	g	g	g	g	%
120	0.675	60	10	308.4	154.5	62.3	29.6	17.1	9.6	0.5	1414.6	1996.6	67.9	4.8
			15	345.6	133.4	56.2	25.6	13.9	6.3	0.4	1408.0	1989.4	64.8	4.6
			20	331.4	139.9	64.1	26.9	13.4	6.9	0.6	1430.6	2013.8	75.9	5.3
			25	304.8	136.7	52.5	28.6	16.8	8.3	0.3	1468.6	2016.6	116.0	7.9
80		90	10	332.4	145.6	62.7	27.3	16.2	6.6	0.5	1419.2	2010.5	68.1	4.8
			15	288.9	152.6	73.2	33.9	23.1	9.8	0.5	1409.2	1991.2	66.3	4.7
			20	286.9	148.3	69.1	31.2	16.3	6.5	0.4	1436.0	1994.7	90.5	6.3
			25	264.3	135.6	60.1	30.3	18.2	8.2	0.6	1478.5	1995.8	128.7	8.7
60		120	10	256.8	136.3	63.9	33.6	16.7	7.3	0.6	1479.1	1994.3	131.7	8.9
			15	238.7	137.1	80.4	30.1	18.7	8.7	0.4	1493.8	2007.9	139.0	9.3
			20	231.6	136.4	70.3	31.1	16.7	9.2	0.6	1510.4	2006.3	160.2	10.6
			25	226.5	116.3	53.6	29.6	14.7	10.3	0.6	1549.7	2001.3	195.3	12.6
48		150	10	241.3	125.1	60.3	26.3	26.6	12.3	0.7	1513.8	2006.4	159.0	10.5
			15	216.2	119.3	59.8	32.5	25.7	14.3	0.7	1534.3	2002.8	181.1	11.8
			20	211.6	114.7	49.2	30.3	15.1	12.4	0.6	1562.6	1996.5	211.0	13.5
			25	208.1	101.1	48.2	22.8	14.5	9.7	0.7	1593.2	1998.3	240.7	15.1

End

Table F-6 Weights of berries collected from different outlets, and the observed screening inaccuracies of the trommel of 4.75-mm apertures at different feed compositions, feed rates and trommel speeds

(Mean of 6 replications)

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Weight of Fines sifted through each Zone: First 15-cm Zone	Second 15-cm Zone	Third 15-cm Zone	Fourth 15-cm Zone	Fifth 15-cm Zone	Sixth 15-cm Zone	Weight of Berries Clogging Apertures	Weight of Tailings	Total Weight	Weight of Undersize Berries in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	g	g	g	g	g	g	g	g	%
120	0.150	60	10	516.4	411.3	306.3	164.5	98.9	45.7	0.4	445.6	1989.1	146.3	32.8
			15	538.9	341.3	312.4	189.2	106.8	58.9	0.5	466.1	2014.1	158.2	33.9
			20	551.9	470.8	264.6	139.6	75.6	43.4	0.6	465.5	2012.0	157.1	33.7
			25	564.9	402.6	272.4	148.3	98.4	53.3	0.7	448.7	1989.3	156.4	34.8
80		90	10	553.1	413.3	264.5	163.8	93.5	68.7	0.4	434.7	1992.0	143.6	33.0
			15	526.3	456.1	253.2	143.4	83.2	72.7	0.6	471.1	2006.6	164.6	34.9
			20	528.2	394.0	256.3	189.6	106.2	56.4	0.6	472.3	2003.6	167.4	35.4
			25	551.3	358.0	238.7	193.4	115.9	71.6	0.7	468.9	1998.5	174.2	37.1
60		120	10	564.3	329.9	286.4	160.9	108.8	69.6	0.5	475.2	1995.6	179.8	37.8
			15	559.9	402.2	271.8	139.0	84.2	51.4	0.5	495.9	2004.9	189.1	38.1
			20	556.1	361.8	265.7	155.2	91.5	64.7	0.4	507.9	2003.3	206.9	40.7
			25	573.3	296.5	230.4	173.7	106.8	69.4	0.8	554.3	2005.2	250.9	45.2
48		150	10	605.1	267.7	226.9	186.8	138.4	76.5	0.6	497.3	1999.3	196.2	39.4
			15	601.5	277.0	227.1	184.4	129.9	73.6	0.8	503.3	1997.6	205.7	40.8
			20	611.3	283.3	254.8	148.7	98.4	44.7	0.8	561.1	2003.1	256.2	45.6
			25	625.9	266.2	230.9	139.7	84.8	51.5	0.7	602.1	2001.8	302.6	50.2
120	0.325	60	10	553.4	362.1	136.6	58.9	40.1	26.9	0.5	825.6	2004.1	176.8	21.4
			15	540.2	346.2	138.7	61.8	43.7	29.6	0.4	827.1	1987.7	184.5	22.3
			20	516.1	334.7	146.3	86.7	46.6	31.8	0.6	851.5	2014.3	195.1	22.9
			25	485.1	326.9	165.1	87.5	53.7	33.5	0.4	849.5	2001.7	202.3	23.8
80		90	10	501.4	301.2	175.8	76.5	53.2	31.3	0.6	864.2	2004.2	217.1	25.1
			15	472.1	315.8	168.6	98.7	50.4	25.7	0.5	864.8	1996.6	216.3	25.0
			20	478.3	296.4	159.5	89.7	57.1	28.1	0.6	884.8	1994.5	235.5	26.6
			25	477.7	308.1	148.1	75.4	54.2	29.2	0.4	909.5	2002.6	254.8	28.0
60		120	10	451.8	293.4	171.6	110.7	63.1	27.2	0.4	888.7	2006.9	237.4	26.7
			15	343.2	258.2	218.8	136.9	101.6	41.9	0.5	896.3	1997.4	246.6	27.5
			20	402.4	261.9	191.2	115.6	78.4	33.7	0.7	911.6	1995.5	261.8	28.7
			25	441.9	273.3	178.6	87.2	56.3	26.2	0.5	939.7	2003.7	285.8	30.4
48		150	10	338.8	253.2	218.2	113.2	81.1	43.2	0.5	953.4	2001.6	302.4	31.7
			15	329.6	268.7	194.4	128.9	83.2	36.7	0.4	957.5	1999.4	309.4	32.3
			20	366.5	260.2	186.2	116.4	64.7	31.2	0.7	972.7	1998.6	325.1	33.4
			25	270.8	268.9	183.4	145.1	68.9	26.6	0.6	1040.5	2004.8	387.3	37.2
120	0.500	60	10	392.7	236.7	124.3	65.4	36.8	17.4	0.5	1123.8	1997.6	121.4	10.8
			15	445.6	237.1	84.7	42.4	21.7	11.2	0.4	1169.3	2012.4	157.9	13.5
			20	441.3	230.5	77.3	43.3	24.0	19.8	0.5	1166.2	2002.9	164.5	14.1
			25	450.6	179.5	86.8	46.3	29.1	17.6	0.3	1176.5	1986.7	183.6	15.6
80		90	10	397.4	196.4	102.3	56.9	33.7	17.7	0.6	1204.8	2009.8	201.3	16.7
			15	386.1	202.4	110.7	52.3	21.7	13.3	0.5	1212.5	1999.5	212.3	17.5
			20	399.3	183.4	91.9	54.3	30.1	13.4	0.5	1234.4	2007.3	229.7	18.6
			25	356.2	203.7	92.6	58.7	25.4	10.9	0.3	1258.1	2005.9	254.2	20.2
60		120	10	410.4	160.3	82.8	41.5	19.5	8.1	0.6	1271.5	1994.7	272.2	21.4
			15	357.9	182.5	96.7	51.4	20.3	11.6	0.6	1277.3	1998.3	282.4	22.1
			20	387.5	174.2	80.1	37.6	21.9	8.8	0.5	1296.5	2007.1	290.5	22.4
			25	331.2	201.2	83.5	45.4	21.4	6.7	0.5	1310.7	2000.6	312.1	23.8
48		150	10	359.8	212.9	86.7	38.9	14.3	8.9	0.7	1274.3	1996.5	279.2	21.9
			15	373.6	185.2	84.6	32.4	22.2	15.3	0.6	1291.5	2005.4	288.1	22.3
			20	379.3	153.2	87.6	46.2	20.9	9.1	0.7	1306.2	2003.2	304.5	23.3
			25	392.4	151.6	69.2	26.7	15.2	8.4	0.6	1340.8	2004.9	340.7	25.4

continued

F-6 continued

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Weight of Fines sifted through each Zone: First 15-cm Zone	Second 15-cm Zone	Third 15-cm Zone	Fourth 15-cm Zone	Fifth 15-cm Zone	Sixth 15-cm Zone	Weight of Berries Clogging Apertures	Weight of Tailings	Total Weight	Weight of Undersize Berries in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	g	g	g	g	g	g	g	g	%
120	0.675	60	10	310.2	125.4	81.6	46.3	28.6	9.2	0.5	1411.5	2013.3	55.1	3.9
			15	308.4	135.4	72.1	39.8	21.3	6.7	0.5	1399.4	1983.6	53.2	3.8
			20	298.7	128.5	62.3	46.2	23.8	7.9	0.5	1421.8	1989.7	74.0	5.2
			25	293.5	126.7	63.4	43.9	26.7	8.9	0.3	1447.7	2011.1	89.8	6.2
80		90	10	300.2	133.7	68.7	41.4	27.2	11.6	0.5	1405.9	1989.2	63.3	4.5
			15	316.0	139.6	59.6	33.6	23.9	12.3	0.5	1423.1	2008.6	66.9	4.7
			20	324.4	131.7	46.7	26.4	15.3	10.6	0.4	1455.3	2010.8	100.4	6.9
			25	307.6	124.4	46.4	23.3	14.2	8.7	0.4	1467.3	1992.3	121.8	8.3
60		120	10	286.8	135.8	56.3	36.8	24.6	10.4	0.4	1456.4	2007.5	103.4	7.1
			15	248.9	143.4	49.4	29.3	31.7	12.6	0.6	1480.5	1996.4	130.3	8.8
			20	235.7	136.7	53.6	32.3	28.8	10.2	0.7	1503.6	2001.6	154.9	10.3
			25	229.0	123.8	45.1	26.5	23.4	6.4	0.6	1550.5	2005.3	200.1	12.9
48		150	10	230.8	111.5	61.3	38.4	31.3	14.1	0.6	1507.2	1995.2	159.8	10.6
			15	251.9	109.2	47.6	43.8	18.6	11.2	0.5	1514.8	1997.6	168.2	11.1
			20	244.7	100.4	51.3	39.6	22.6	10.2	0.7	1534.8	2004.3	182.7	11.9
			25	231.2	99.8	63.4	23.9	17.2	7.6	0.4	1555.3	1998.8	203.8	13.1

Table F-7 Zone-wise screening percentage of fines at various trommel speeds, feed rates and feed compositions of the three trommels

(*Mean of 6 replications*)

Feed Composition	Feed Rate	Trommel Speed	Zone-wise Screening Percentage of Fines, %																	
			Aperture Diameter = 4.00 mm						Aperture Diameter = 4.25 mm						Aperture Diameter = 4.75 mm					
			Distance from Inlet, cm						Distance from Inlet, cm						Distance from Inlet, cm					
			0-15	15-30	30-45	45-60	60-75	75-90	0-15	15-30	30-45	45-60	60-75	75-90	0-15	15-30	30-45	45-60	60-75	75-90
(-)	kg/h	r/min	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0.150	60	10	31.93	30.00	38.97	36.62	34.87	33.85	32.86	35.41	43.24	36.12	26.81	24.85	30.57	35.06	40.21	36.12	34.00	23.80
		15	29.62	33.59	42.21	38.41	29.83	28.79	31.40	29.83	37.91	34.80	32.38	34.14	31.59	29.25	37.84	36.87	32.97	27.13
		20	30.60	29.94	39.79	36.54	33.44	25.62	32.21	34.62	41.85	33.57	26.11	23.24	32.41	40.90	38.89	33.58	27.38	21.65
		25	31.65	27.86	38.39	31.89	31.64	28.11	33.79	32.19	40.66	32.00	24.69	23.03	33.30	35.58	37.38	32.49	31.94	25.42
	90	10	31.24	31.06	36.23	36.28	29.52	28.30	34.13	31.22	36.32	34.34	31.50	32.58	32.53	36.02	36.03	34.88	30.58	32.36
		15	29.45	36.86	37.73	35.07	29.22	28.11	33.51	35.82	41.65	34.12	27.41	24.64	30.97	38.88	35.31	30.91	25.96	30.64
		20	30.87	27.68	33.06	37.97	31.79	23.61	31.81	34.25	41.74	34.01	26.70	27.09	31.11	33.68	33.03	36.49	32.18	25.20
		25	31.44	26.47	30.11	33.83	29.95	22.77	33.03	32.66	40.77	30.82	25.25	23.68	32.37	31.08	30.07	34.84	32.04	29.13
	120	10	30.61	25.12	31.75	33.84	35.95	35.07	32.48	28.99	39.24	32.02	34.66	27.84	33.20	29.06	35.56	31.00	30.37	27.91
		15	29.98	26.34	30.49	32.96	34.71	31.33	34.52	27.69	31.27	31.32	33.36	30.11	32.98	35.35	36.95	29.98	25.93	21.37
		20	28.38	26.40	28.44	33.62	32.93	30.75	32.11	24.48	32.47	29.90	32.69	22.12	32.68	31.58	33.89	29.94	25.20	23.82
		25	26.13	26.69	26.34	33.55	30.77	30.78	27.62	32.30	34.28	27.88	28.25	18.49	33.70	26.23	27.72	28.91	25.01	21.67
	150	10	27.93	26.28	28.11	36.11	33.69	34.58	27.96	33.53	37.84	33.04	36.50	29.11	35.64	24.50	27.51	31.24	33.67	28.05
		15	24.39	26.38	26.00	36.57	33.38	36.96	31.92	27.03	35.23	32.76	35.23	27.42	35.40	25.23	27.67	31.06	31.74	26.35
		20	23.99	24.76	23.64	32.18	28.04	29.31	28.95	26.67	32.17	29.73	32.31	27.43	36.01	26.08	31.74	27.14	24.64	14.86
		25	21.65	19.76	20.21	29.16	25.74	26.99	25.78	22.43	28.05	25.99	27.93	22.20	36.78	24.75	28.52	24.14	19.32	14.54
0.325	60	10	41.63	43.59	37.74	22.76	13.71	7.70	38.04	41.71	32.45	27.21	24.22	13.99	40.85	45.18	31.09	19.46	16.45	13.21
		15	41.00	42.31	34.61	23.11	16.52	8.63	40.58	43.26	35.63	24.53	17.79	9.77	40.17	43.03	30.26	19.34	16.95	13.83
		20	40.76	38.70	30.78	24.05	17.67	9.14	38.46	40.38	31.88	24.46	18.87	10.16	38.02	39.79	28.88	24.07	17.04	14.01
		25	38.45	35.10	26.90	22.43	17.70	10.12	35.44	35.04	29.61	24.74	18.62	10.83	35.82	37.62	30.46	23.21	18.55	14.21
	90	10	37.43	33.73	32.69	25.99	17.25	7.22	34.97	38.01	30.29	24.75	20.11	12.94	36.96	35.22	31.74	20.23	17.64	12.60
		15	35.82	32.82	31.74	22.23	15.12	7.28	34.86	36.37	33.22	24.25	17.41	8.80	35.03	36.07	30.12	25.24	17.24	10.62
		20	37.10	31.26	27.16	19.90	14.78	7.01	37.33	35.58	29.60	22.25	17.14	8.61	35.57	34.21	27.99	21.86	17.80	10.66
		25	36.23	29.91	25.38	17.49	14.26	7.04	34.92	36.22	27.57	20.19	16.59	8.99	35.45	35.42	26.37	18.23	16.03	10.28
	120	10	34.35	28.02	27.36	20.06	19.61	9.64	26.82	32.06	30.07	28.74	19.86	11.62	33.34	32.48	28.13	25.25	19.26	10.28
		15	31.30	23.87	26.46	19.73	20.48	5.85	26.64	27.27	29.40	27.18	20.05	13.37	25.48	25.72	29.34	25.98	26.04	14.52
		20	30.99	27.07	24.54	19.41	13.36	6.44	27.57	32.11	29.54	22.79	17.87	10.21	29.92	27.78	28.09	23.62	20.97	11.40
		25	31.46	26.94	24.22	17.30	12.14	5.84	31.03	32.78	26.87	19.99	15.11	6.94	32.75	30.12	28.17	19.14	15.29	8.40
	150	10	30.22	27.87	27.86	17.01	18.24	10.30	29.64	32.24	26.79	20.06	16.46	10.01	25.09	25.04	28.78	20.97	19.01	12.50
		15	28.37	26.25	24.47	17.76	14.48	5.52	28.20	28.18	27.29	20.10	16.69	8.10	24.40	26.31	25.83	23.09	19.38	10.60
		20	25.30	27.80	23.58	10.07	16.31	7.59	25.53	29.67	26.10	20.82	16.26	10.45	27.14	26.45	25.73	21.66	15.37	8.76
		25	25.86	27.09	21.03	11.42	10.70	7.81	25.73	28.77	24.34	19.86	16.28	9.91	20.04	24.89	22.61	23.11	14.27	6.43

continued

F-7 ... continued ...

Feed Composition	Feed Rate	Trommel Speed	Zone-wise Screening Percentage of Fines, %																	
			Aperture Diameter = 4.00 mm						Aperture Diameter = 4.25 mm						Aperture Diameter = 4.75 mm					
			Distance from Inlet, cm						Distance from Inlet, cm						Distance from Inlet, cm					
			0-15	15-30	30-45	45-60	60-75	75-90	0-15	15-30	30-45	45-60	60-75	75-90	0-15	15-30	30-45	45-60	60-75	75-90
(-)	kg/h	r/min	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0.500	60	10	51.67	45.80	34.50	21.93	15.63	12.15	43.22	41.82	34.53	24.74	18.28	10.04	39.48	39.32	34.03	27.14	20.96	12.54
		15	50.35	44.63	30.40	18.79	14.30	9.05	50.35	41.72	33.02	22.32	13.93	7.98	44.53	42.72	26.64	18.18	11.37	6.62
		20	47.87	42.37	27.20	18.24	12.62	10.51	49.85	41.05	26.79	19.90	13.67	9.46	44.10	41.20	23.50	17.21	11.52	10.74
		25	43.33	40.74	24.62	16.95	11.30	8.05	47.37	40.04	24.90	18.52	13.80	9.21	45.35	33.06	23.89	16.74	12.64	8.75
	90	10	42.96	40.29	28.99	21.99	13.89	10.97	45.12	36.60	24.43	20.16	11.44	6.32	39.51	32.29	24.84	18.38	13.34	8.08
		15	41.19	40.00	26.98	23.08	16.43	10.46	43.32	35.16	24.34	16.77	13.09	10.37	38.66	33.03	26.98	17.46	8.77	5.90
		20	40.51	40.82	26.33	18.28	14.27	8.79	42.24	32.24	23.47	17.93	12.51	7.59	39.85	30.42	21.91	16.58	11.02	5.51
		25	39.25	38.98	22.92	15.41	12.32	7.90	42.45	30.47	21.91	14.72	10.07	6.00	35.56	31.56	20.96	16.81	8.74	4.11
	120	10	38.86	39.51	26.20	19.59	15.07	13.16	37.10	32.26	31.88	21.32	12.37	6.41	41.25	27.43	19.52	12.16	6.50	2.89
		15	36.93	35.38	24.41	19.88	15.99	11.22	40.87	32.76	27.91	17.55	10.52	5.47	35.69	28.30	20.91	14.06	6.46	3.95
		20	34.07	32.04	24.97	20.41	11.82	9.43	38.53	26.98	24.21	16.39	10.79	8.34	38.73	28.41	18.25	10.48	6.82	2.94
		25	32.68	31.53	21.56	15.43	7.98	6.29	39.63	25.94	19.35	13.74	7.62	3.78	33.07	30.02	17.80	11.77	6.29	2.10
	150	10	31.76	34.03	26.82	21.24	14.27	10.97	43.21	30.61	21.41	12.72	8.28	5.52	35.95	33.22	20.26	11.40	4.73	3.09
		15	30.75	34.12	24.52	13.53	11.86	13.76	40.00	33.36	21.77	11.79	7.20	4.84	37.31	29.50	19.11	9.05	6.82	5.04
		20	30.37	32.46	22.12	11.30	12.02	7.48	38.72	35.19	13.59	9.57	5.94	3.46	37.90	24.65	18.71	12.14	6.25	2.90
		25	27.59	27.77	19.04	10.29	9.23	4.52	37.34	26.32	16.75	11.19	7.16	3.56	39.08	24.78	15.04	6.83	4.17	2.41
0.675	60	10	48.67	42.21	34.53	26.41	19.43	13.97	47.49	45.31	33.40	23.83	18.08	12.39	47.26	36.22	36.96	33.26	30.79	14.31
		15	55.46	44.35	32.17	21.01	17.69	11.37	53.52	44.44	33.69	23.15	16.35	8.86	48.42	41.22	37.34	32.89	26.23	11.19
		20	53.01	46.22	31.29	22.18	15.18	9.15	50.33	42.77	34.24	21.85	13.93	8.33	46.57	37.50	29.08	30.41	22.52	9.65
		25	48.10	40.26	30.10	17.30	12.11	7.90	45.92	38.09	23.63	16.85	11.91	6.68	44.95	35.25	27.25	25.93	21.29	9.02
	90	10	43.66	39.15	38.54	34.45	24.16	17.03	50.45	44.59	34.66	23.10	17.82	8.84	46.46	38.65	32.38	28.85	26.64	15.49
		15	48.31	41.16	31.69	24.78	24.24	12.13	44.60	42.52	35.48	25.47	23.29	12.88	48.47	41.56	30.36	24.58	23.18	15.53
		20	50.45	41.75	25.47	19.68	13.55	9.03	44.22	40.98	32.35	21.59	14.39	6.70	49.49	39.78	23.42	17.29	12.11	9.55
		25	46.37	37.49	20.60	14.15	8.81	7.10	40.95	35.58	24.48	16.34	11.73	5.99	47.59	36.72	21.64	13.87	9.81	6.67
	120	10	44.59	37.93	34.09	21.65	16.18	9.86	39.73	34.99	25.24	17.75	10.73	5.25	43.85	36.97	24.32	21.00	17.77	9.14
		15	43.27	34.11	33.22	23.04	16.46	10.92	36.57	33.12	29.04	15.32	11.24	5.89	38.55	36.15	19.50	14.37	18.16	8.82
		20	39.58	32.99	30.37	20.16	16.08	8.81	35.33	32.18	24.45	14.32	8.97	5.43	36.14	32.82	19.16	14.28	14.85	6.18
		25	40.69	31.99	22.27	15.56	10.73	4.44	35.05	27.70	17.66	11.84	6.67	5.01	35.00	29.11	14.96	10.34	10.18	3.10
	150	10	40.63	31.68	25.98	19.34	14.85	9.91	37.07	30.54	21.20	11.73	13.44	7.18	35.66	26.78	20.10	15.76	15.25	8.11
		15	33.08	30.40	27.31	18.69	18.61	10.28	33.32	27.57	19.08	12.82	11.62	7.32	38.72	27.40	16.45	18.11	9.39	6.24
		20	35.75	28.49	24.57	12.58	10.40	7.15	32.84	26.51	15.47	11.27	6.33	5.55	37.56	24.68	16.74	15.52	10.49	5.29
		25	33.30	24.59	15.46	12.55	9.05	3.86	32.26	23.14	14.35	7.92	5.47	3.87	35.74	24.01	20.07	9.47	7.52	3.60

End

Table F-8 Clogging indices of the trommel of 4.00-mm apertures at different feed compositions, feed rates, and trommel speeds

Feed Rate kg/h	Replication No.	Clogging Index, %															
		Feed Composition, (-)															
		0.150				0.325				0.500				0.675			
		Trommel Speed, r/min															
		10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	R1	0.04	0.08	0.02	0.14	0.12	0.04	0.08	0.02	0.12	0.06	0.10	0.08	0.12	0.12	0.12	0.14
60	R2	0.12	0.12	0.06	0.12	0.06	0.12	0.06	0.04	0.16	0.10	0.06	0.12	0.18	0.14	0.10	0.12
60	R3	0.10	0.12	0.10	0.08	0.08	0.10	0.06	0.08	0.14	0.08	0.14	0.16	0.12	0.10	0.08	0.16
60	R4	0.08	0.14	0.08	0.10	0.10	0.10	0.12	0.04	0.10	0.12	0.08	0.08	0.16	0.12	0.12	0.18
60	R5	0.08	0.08	0.08	0.12	0.10	0.04	0.02	0.10	0.12	0.06	0.08	0.12	0.14	0.14	0.14	0.10
60	R6	0.10	0.04	0.06	0.12	0.04	0.06	0.04	0.08	0.08	0.10	0.06	0.10	0.21	0.14	0.08	0.14
	Mean	0.09	0.10	0.07	0.12	0.09	0.08	0.06	0.06	0.12	0.09	0.09	0.11	0.16	0.13	0.11	0.14
90	R1	0.18	0.08	0.12	0.08	0.12	0.04	0.10	0.08	0.10	0.06	0.06	0.10	0.10	0.18	0.10	0.14
90	R2	0.12	0.14	0.12	0.12	0.10	0.06	0.12	0.12	0.08	0.08	0.04	0.12	0.16	0.14	0.12	0.14
90	R3	0.12	0.16	0.12	0.14	0.08	0.10	0.12	0.12	0.14	0.12	0.10	0.10	0.10	0.10	0.14	0.18
90	R4	0.10	0.16	0.10	0.12	0.04	0.06	0.10	0.12	0.12	0.08	0.08	0.08	0.12	0.08	0.14	0.12
90	R5	0.08	0.12	0.18	0.10	0.08	0.06	0.06	0.08	0.10	0.10	0.06	0.08	0.14	0.14	0.10	0.16
90	R6	0.10	0.12	0.14	0.12	0.04	0.04	0.06	0.08	0.06	0.08	0.06	0.08	0.12	0.18	0.16	0.12
	Mean	0.12	0.13	0.13	0.12	0.08	0.06	0.10	0.10	0.10	0.09	0.07	0.10	0.13	0.14	0.13	0.15
120	R1	0.12	0.08	0.14	0.18	0.10	0.06	0.12	0.16	0.08	0.04	0.06	0.12	0.16	0.14	0.08	0.18
120	R2	0.14	0.12	0.12	0.08	0.14	0.12	0.16	0.18	0.10	0.08	0.06	0.14	0.21	0.16	0.14	0.14
120	R3	0.10	0.16	0.16	0.10	0.12	0.08	0.12	0.10	0.10	0.06	0.04	0.06	0.12	0.10	0.12	0.18
120	R4	0.12	0.10	0.10	0.16	0.04	0.06	0.08	0.10	0.08	0.04	0.12	0.08	0.14	0.08	0.10	0.12
120	R5	0.14	0.12	0.12	0.12	0.08	0.12	0.08	0.12	0.10	0.04	0.10	0.10	0.16	0.14	0.08	0.14
120	R6	0.16	0.12	0.08	0.14	0.04	0.12	0.18	0.08	0.04	0.10	0.06	0.08	0.16	0.18	0.14	0.16
	Mean	0.13	0.12	0.12	0.13	0.09	0.10	0.13	0.13	0.09	0.06	0.08	0.10	0.16	0.14	0.11	0.16
150	R1	0.14	0.12	0.14	0.12	0.18	0.14	0.23	0.10	0.21	0.18	0.08	0.08	0.18	0.14	0.08	0.18
150	R2	0.12	0.08	0.12	0.10	0.18	0.14	0.16	0.12	0.10	0.10	0.10	0.16	0.23	0.23	0.12	0.25
150	R3	0.04	0.16	0.10	0.10	0.10	0.10	0.12	0.14	0.18	0.10	0.16	0.14	0.16	0.21	0.14	0.12
150	R4	0.06	0.10	0.08	0.12	0.12	0.08	0.12	0.16	0.12	0.18	0.14	0.12	0.12	0.18	0.16	0.14
150	R5	0.12	0.12	0.12	0.08	0.14	0.16	0.18	0.08	0.18	0.16	0.10	0.14	0.16	0.14	0.14	0.12
150	R6	0.08	0.10	0.12	0.06	0.14	0.21	0.14	0.12	0.16	0.14	0.18	0.12	0.18	0.12	0.12	0.16
	Mean	0.10	0.12	0.12	0.10	0.15	0.14	0.16	0.12	0.16	0.15	0.13	0.13	0.17	0.17	0.13	0.16

Table F-9 Clogging indices of the trommel of 4.25-mm apertures at different feed compositions, feed rates, and trommel speeds

Feed Rate	Replication No.	Clogging Index, %															
		Feed Composition, (-)															
		0.150				0.325				0.500				0.675			
		Trommel Speed, r/min															
kg/h		10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	R1	0.25	0.10	0.16	0.16	0.14	0.10	0.12	0.14	0.06	0.04	0.06	0.10	0.06	0.12	0.12	0.08
60	R2	0.12	0.12	0.08	0.10	0.12	0.12	0.12	0.06	0.10	0.06	0.08	0.12	0.12	0.06	0.08	0.06
60	R3	0.16	0.06	0.14	0.12	0.12	0.18	0.08	0.06	0.06	0.10	0.12	0.16	0.08	0.08	0.10	0.08
60	R4	0.18	0.10	0.12	0.16	0.08	0.16	0.08	0.10	0.04	0.02	0.10	0.08	0.10	0.12	0.16	0.04
60	R5	0.14	0.10	0.16	0.14	0.12	0.14	0.10	0.06	0.04	0.10	0.14	0.12	0.08	0.06	0.10	0.06
60	R6	0.16	0.12	0.16	0.08	0.06	0.14	0.16	0.10	0.08	0.12	0.16	0.10	0.14	0.08	0.10	0.08
	Mean	0.17	0.10	0.14	0.13	0.11	0.14	0.11	0.09	0.06	0.08	0.11	0.12	0.10	0.09	0.11	0.07
90	R1	0.12	0.02	0.12	0.04	0.04	0.14	0.12	0.08	0.04	0.04	0.08	0.02	0.12	0.14	0.04	0.08
90	R2	0.08	0.10	0.12	0.12	0.02	0.12	0.10	0.10	0.10	0.02	0.08	0.06	0.08	0.10	0.12	0.18
90	R3	0.18	0.12	0.08	0.10	0.12	0.06	0.10	0.12	0.08	0.06	0.10	0.10	0.10	0.08	0.06	0.16
90	R4	0.16	0.04	0.16	0.12	0.10	0.10	0.12	0.08	0.06	0.10	0.06	0.04	0.14	0.16	0.10	0.10
90	R5	0.18	0.06	0.14	0.08	0.06	0.08	0.06	0.16	0.04	0.08	0.04	0.02	0.06	0.08	0.08	0.08
90	R6	0.10	0.12	0.10	0.12	0.08	0.10	0.16	0.16	0.04	0.06	0.06	0.10	0.08	0.08	0.06	0.12
	Mean	0.14	0.08	0.12	0.10	0.07	0.10	0.11	0.12	0.06	0.06	0.07	0.06	0.10	0.11	0.08	0.12
120	R1	0.12	0.16	0.12	0.18	0.14	0.16	0.23	0.14	0.12	0.14	0.12	0.14	0.16	0.08	0.18	0.16
120	R2	0.16	0.08	0.06	0.14	0.12	0.08	0.10	0.12	0.14	0.10	0.18	0.12	0.06	0.12	0.08	0.08
120	R3	0.06	0.12	0.10	0.06	0.06	0.12	0.16	0.10	0.08	0.12	0.21	0.10	0.08	0.06	0.12	0.10
120	R4	0.10	0.10	0.12	0.10	0.08	0.16	0.18	0.16	0.12	0.12	0.10	0.12	0.14	0.04	0.16	0.12
120	R5	0.12	0.08	0.08	0.16	0.12	0.10	0.14	0.18	0.16	0.14	0.12	0.06	0.14	0.10	0.08	0.14
120	R6	0.06	0.16	0.12	0.16	0.16	0.10	0.12	0.12	0.16	0.08	0.12	0.08	0.12	0.08	0.10	0.08
	Mean	0.11	0.12	0.10	0.14	0.12	0.12	0.16	0.14	0.13	0.12	0.14	0.11	0.12	0.08	0.12	0.12
150	R1	0.14	0.14	0.04	0.16	0.23	0.16	0.14	0.14	0.10	0.08	0.14	0.08	0.18	0.14	0.08	0.18
150	R2	0.12	0.12	0.10	0.12	0.12	0.10	0.16	0.12	0.12	0.06	0.04	0.12	0.14	0.21	0.06	0.21
150	R3	0.10	0.06	0.12	0.08	0.14	0.08	0.12	0.10	0.14	0.04	0.12	0.06	0.12	0.16	0.12	0.12
150	R4	0.16	0.10	0.02	0.14	0.16	0.12	0.10	0.12	0.06	0.12	0.10	0.10	0.16	0.12	0.14	0.12
150	R5	0.10	0.10	0.06	0.16	0.10	0.16	0.12	0.16	0.14	0.08	0.12	0.14	0.10	0.10	0.16	0.10
150	R6	0.06	0.08	0.12	0.06	0.10	0.16	0.10	0.08	0.10	0.10	0.16	0.12	0.14	0.12	0.10	0.14
	Mean	0.12	0.10	0.08	0.12	0.14	0.13	0.13	0.12	0.11	0.08	0.12	0.11	0.14	0.14	0.11	0.15

Table F-10 Clogging indices of the trommel of 4.75-mm apertures at different feed compositions, feed rates, and trommel speeds

Feed Rate	Replication No.	Clogging Index, %															
		Feed Composition, (-)															
		0.150				0.325				0.500				0.675			
		Trommel Speed, r/min															
kg/h		10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	R1	0.04	0.10	0.18	0.18	0.06	0.04	0.18	0.12	0.08	0.10	0.10	0.06	0.12	0.06	0.10	0.02
60	R2	0.06	0.10	0.10	0.14	0.10	0.02	0.06	0.08	0.16	0.08	0.08	0.10	0.06	0.12	0.10	0.06
60	R3	0.10	0.06	0.12	0.12	0.12	0.12	0.14	0.06	0.06	0.04	0.06	0.02	0.10	0.06	0.12	0.10
60	R4	0.12	0.08	0.08	0.10	0.08	0.08	0.12	0.06	0.14	0.12	0.12	0.04	0.08	0.08	0.06	0.04
60	R5	0.06	0.12	0.16	0.12	0.06	0.12	0.06	0.12	0.12	0.02	0.08	0.08	0.12	0.12	0.08	0.02
60	R6	0.08	0.16	0.10	0.12	0.12	0.10	0.10	0.06	0.08	0.08	0.10	0.06	0.12	0.14	0.12	0.08
	Mean	0.08	0.11	0.13	0.13	0.09	0.08	0.11	0.09	0.11	0.08	0.09	0.06	0.10	0.10	0.10	0.05
90	R1	0.08	0.18	0.06	0.12	0.14	0.12	0.18	0.06	0.10	0.08	0.12	0.02	0.10	0.14	0.12	0.06
90	R2	0.12	0.10	0.12	0.08	0.12	0.06	0.08	0.12	0.06	0.12	0.04	0.06	0.06	0.12	0.08	0.08
90	R3	0.10	0.12	0.14	0.18	0.06	0.10	0.12	0.08	0.04	0.16	0.10	0.10	0.12	0.08	0.04	0.10
90	R4	0.06	0.08	0.12	0.16	0.14	0.12	0.16	0.10	0.14	0.10	0.06	0.08	0.08	0.10	0.10	0.08
90	R5	0.08	0.12	0.12	0.21	0.08	0.06	0.10	0.06	0.16	0.08	0.12	0.06	0.10	0.08	0.08	0.06
90	R6	0.06	0.14	0.14	0.10	0.12	0.08	0.12	0.06	0.16	0.08	0.12	0.08	0.12	0.08	0.10	0.10
	Mean	0.09	0.13	0.12	0.14	0.11	0.09	0.13	0.08	0.11	0.11	0.10	0.07	0.10	0.10	0.09	0.08
120	R1	0.06	0.08	0.10	0.25	0.02	0.14	0.18	0.04	0.18	0.06	0.16	0.14	0.06	0.18	0.14	0.08
120	R2	0.08	0.12	0.12	0.16	0.06	0.12	0.08	0.10	0.16	0.10	0.08	0.06	0.10	0.08	0.18	0.12
120	R3	0.12	0.10	0.08	0.14	0.12	0.10	0.21	0.12	0.12	0.12	0.12	0.12	0.08	0.12	0.08	0.16
120	R4	0.14	0.04	0.10	0.12	0.08	0.12	0.12	0.14	0.10	0.16	0.06	0.08	0.12	0.16	0.12	0.06
120	R5	0.10	0.12	0.06	0.12	0.04	0.08	0.12	0.06	0.08	0.06	0.08	0.10	0.08	0.10	0.16	0.10
120	R6	0.12	0.14	0.06	0.12	0.12	0.08	0.14	0.10	0.08	0.16	0.12	0.12	0.04	0.12	0.10	0.14
	Mean	0.11	0.10	0.09	0.15	0.08	0.11	0.14	0.10	0.12	0.11	0.11	0.11	0.08	0.13	0.13	0.11
150	R1	0.16	0.14	0.12	0.18	0.12	0.04	0.10	0.12	0.16	0.10	0.18	0.08	0.14	0.08	0.08	0.02
150	R2	0.12	0.16	0.23	0.14	0.06	0.10	0.12	0.10	0.12	0.12	0.08	0.14	0.12	0.06	0.16	0.10
150	R3	0.08	0.23	0.12	0.12	0.04	0.12	0.08	0.12	0.08	0.08	0.12	0.12	0.10	0.12	0.14	0.08
150	R4	0.06	0.12	0.14	0.16	0.08	0.08	0.18	0.10	0.18	0.06	0.16	0.10	0.16	0.10	0.12	0.06
150	R5	0.16	0.21	0.12	0.10	0.12	0.06	0.18	0.14	0.14	0.16	0.12	0.12	0.18	0.08	0.14	0.04
150	R6	0.12	0.14	0.18	0.12	0.14	0.06	0.16	0.12	0.12	0.16	0.14	0.16	0.06	0.14	0.18	0.12
	Mean	0.12	0.17	0.15	0.14	0.10	0.08	0.14	0.12	0.14	0.12	0.14	0.12	0.13	0.10	0.14	0.07

Table G-1 Screening inaccuracies of the three trommels at different feed compositions, feed rates and trommel speeds

(Mean of 3 replications)

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Aperture Diameter: 4.00 mm			Aperture Diameter: 4.25 mm			Aperture Diameter: 4.75 mm		
				Total Weight of Tailings	Weight of Fines in Tailings	Screening Inaccuracy	Total Weight of Tailings	Weight of Fines in Tailings	Screening Inaccuracy	Total Weight of Tailings	Weight of Fines in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	%	g	g	%	g	g	%
120	0.150	60	10	443.4	116.6	26.3	436.8	164.7	37.7	456.9	135.7	29.7
			15	436.8	145.0	33.2	447.1	159.7	35.7	456.2	167.4	36.7
			20	441.5	166.4	37.7	468.9	187.9	40.1	488.4	176.3	36.1
			25	487.7	156.5	32.1	476.7	189.3	39.7	462.7	156.4	33.8
80		90	10	487.1	160.3	32.9	435.2	169.9	39.0	413.6	124.5	30.1
			15	456.5	174.4	38.2	461.3	145.2	31.5	452.5	170.6	37.7
			20	468.0	160.1	34.2	448.9	152.1	33.9	471.5	179.6	38.1
			25	536.8	234.0	43.6	486.1	162.6	33.4	459.1	167.6	36.5
60		120	10	484.2	164.1	33.9	452.2	164.6	36.4	496.5	184.2	37.1
			15	468.9	157.6	33.6	478.8	165.8	34.6	501.6	219.2	43.7
			20	498.4	216.3	43.4	501.9	208.8	41.6	513.2	213.0	41.5
			25	501.2	201.5	40.2	506.5	246.9	48.7	532.2	264.0	49.6
48		150	10	479.4	164.0	34.2	467.7	171.2	36.6	465.7	163.9	35.2
			15	499.6	215.3	43.1	487.6	169.4	34.7	489.5	214.4	43.8
			20	528.7	260.6	49.3	504.7	214.6	42.5	531.1	220.9	41.6
			25	597.1	339.2	56.8	567.1	312.0	55.0	577.4	265.1	45.9
120	0.325	60	10	843.1	145.2	17.2	789.0	144.4	18.3	809.9	149.2	18.4
			15	813.9	202.7	24.9	798.8	153.7	19.2	821.4	211.9	25.8
			20	809.3	205.6	25.4	819.3	204.2	24.9	879.3	204.9	23.3
			25	880.2	189.2	21.5	858.7	228.7	26.6	846.4	216.7	25.6
80		90	10	854.6	186.3	21.8	869.4	197.4	22.7	859.2	182.2	21.2
			15	891.0	237.1	26.6	861.9	223.2	25.9	839.6	204.9	24.4
			20	909.6	234.7	25.8	873.5	236.4	27.1	898.3	241.6	26.9
			25	973.1	312.4	32.1	881.0	239.0	27.1	925.8	281.4	30.4
60		120	10	903.5	247.6	27.4	898.7	248.4	27.6	903.7	231.3	25.6
			15	946.3	267.8	28.3	915.5	287.2	31.4	901.3	265.0	29.4
			20	980.7	369.7	37.7	914.4	276.9	30.3	925.1	279.4	30.2
			25	981.3	339.5	34.6	939.9	312.3	33.2	930.4	309.8	33.3
48		150	10	948.1	258.8	27.3	927.6	268.3	28.9	947.2	290.8	30.7
			15	1058.9	386.5	36.5	953.2	298.4	31.3	946.6	286.8	30.3
			20	1067.7	357.7	33.5	950.8	318.8	33.5	943.7	346.3	36.7
			25	1089.6	402.1	36.9	984.6	337.3	34.3	988.6	393.5	39.8
120	0.500	60	10	1152.6	94.5	8.2	1178.3	143.8	12.2	1094.7	96.3	8.8
			15	1101.0	109.0	9.9	1087.4	146.2	13.4	1189.5	134.4	11.3
			20	1109.9	168.7	15.2	1078.7	124.9	11.6	1181.7	157.2	13.3
			25	1189.8	151.1	12.7	1208.4	179.6	14.9	1194.9	199.5	16.7
80		90	10	1184.2	137.4	11.6	1145.6	209.7	18.3	1265.9	220.3	17.4
			15	1189.7	124.9	10.5	1114.8	175.5	15.7	1196.6	175.9	14.7
			20	1126.3	125.3	11.1	1245.3	162.6	13.1	1239.0	234.2	18.9
			25	1213.4	165.1	13.6	1217.8	237.3	19.5	1246.2	301.6	24.2
60		120	10	1187.7	146.1	12.3	1256.5	146.5	11.7	1263.0	313.2	24.8
			15	1193.5	176.6	14.8	1239.0	198.7	16.0	1232.1	247.7	20.1
			20	1264.2	188.4	14.9	1218.6	246.9	20.3	1323.8	259.5	19.6
			25	1253.4	269.5	21.5	1239.9	265.3	21.4	1301.6	355.3	27.3
48		150	10	1187.9	156.8	13.2	1346.1	224.8	16.7	1297.7	305.4	23.5
			15	1212.2	214.6	17.7	1287.9	221.1	17.2	1309.6	301.2	23.0
			20	1299.3	245.6	18.9	1261.6	289.7	23.0	1346.3	290.8	21.6
			25	1312.8	365.7	27.9	1265.3	312.6	24.7	1374.8	369.8	26.9

(Continued ...)

G-1 … continued ..

Screening Time	Feed Composition	Feed Rate	Trommel Speed	Aperture Diameter: 4.00 mm			Aperture Diameter: 4.25 mm			Aperture Diameter: 4.75 mm		
				Total Weight of Tailings	Weight of Fines in Tailings	Screening Inaccuracy	Total Weight of Tailings	Weight of Fines in Tailings	Screening Inaccuracy	Total Weight of Tailings	Weight of Fines in Tailings	Screening Inaccuracy
s	(-)	kg/h	r/min	g	g	%	g	g	%	g	g	%
120	0.675	60	10	1384.2	56.8	4.1	1408.5	54.5	3.9	1456.1	64.1	4.4
			15	1438.7	61.9	4.3	1426.8	59.6	4.2	1432.4	51.6	3.6
			20	1420.7	58.2	4.1	1416.7	81.4	5.7	1396.7	65.6	4.7
			25	1498.0	88.4	5.9	1478.0	117.7	8.0	1469.5	83.8	5.7
80		90	10	1372.5	65.9	4.8	1401.4	62.1	4.4	1388.8	62.5	4.5
			15	1401.4	60.3	4.3	1394.8	61.1	4.4	1459.9	61.3	4.2
			20	1456.6	115.1	7.9	1418.3	98.4	6.9	1448.7	95.6	6.6
			25	1492.9	155.3	10.4	1439.9	115.8	8.0	1476.1	115.1	7.8
60		120	10	1428.7	75.7	5.3	1432.5	122.2	8.5	1481.9	124.5	8.4
			15	1459.5	96.3	6.6	1467.3	123.8	8.4	1501.5	147.1	9.8
			20	1436.5	113.5	7.9	1528.4	151.7	9.9	1483.6	182.5	12.3
			25	1478.4	168.5	11.4	1568.7	183.2	11.7	1589.4	186.0	11.7
48		150	10	1498.2	188.8	12.6	1546.4	143.8	9.3	1513.3	171.7	11.3
			15	1524.8	205.8	13.5	1514.7	173.1	11.4	1567.6	194.4	12.4
			20	1502.6	141.2	9.4	1558.3	226.6	14.5	1529.2	209.5	13.7
			25	1554.9	164.8	10.6	1617.9	248.7	15.4	1567.8	224.2	14.3

End

Table H-1 Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, and trommel speed, on screening inaccuracy of the trommel of 4.25-mm apertures

Feed Composition (F_C) (-)	Mean Screening Inaccuracy, %								
	Feed Rate (F_T), kg/h				Trommel Speed (N), r/min				Mean
	60	90	120	150	10	15	20	25	
0.150	34.73	34.68	39.18	40.23	33.56	35.10	38.28	41.89	37.21
0.325	21.68	25.26	28.82	32.01	24.93	26.28	27.32	29.24	26.94
0.500	11.63	16.25	18.22	20.89	15.08	15.46	17.33	19.12	16.74
0.675	5.63	6.12	10.34	12.69	7.22	7.57	8.93	11.06	8.70
Feed Rate (F_T), kg/h									
60	-	-	-	-	16.96	17.18	18.84	20.68	18.42
90	-	-	-	-	19.03	19.63	20.64	23.03	20.58
120	-	-	-	-	21.42	22.70	25.18	27.25	24.14
150	-	-	-	-	23.38	24.88	27.20	30.35	26.46
Mean	18.42	20.58	24.14	26.46	20.20	21.10	22.96	25.33	

Significance Level	LSD *for*					
	F_C	F_T	N	$F_C \times F_T$	$F_C \times N$	$F_T \times N$
0.01	0.81	0.81	0.81	1.01	1.01	1.01
0.05	0.42	0.42	0.42	0.66	0.66	0.66

Table H-2 Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, and trommel speed, on screening inaccuracy of the trommel of 4.75-mm apertures

Feed Composition (F_C) (-)	Mean Screening Inaccuracy, %								
	Feed Rate (F_T), kg/h				Trommel Speed (N), r/min				Mean
	60	90	120	150	10	15	20	25	
0.150	33.78	35.07	40.44	43.99	35.71	36.92	38.84	41.82	38.32
0.325	22.60	26.16	28.32	33.64	26.20	26.77	27.89	29.85	27.68
0.500	13.50	18.25	22.43	23.22	17.73	18.85	19.60	21.21	19.35
0.675	4.78	6.09	9.75	11.66	6.51	7.08	8.57	10.12	8.07
Feed Rate (F_T), kg/h									
60	-	-	-	-	17.21	18.35	18.99	20.10	18.66
90	-	-	-	-	19.83	20.52	21.86	23.36	21.39
120	-	-	-	-	23.24	24.14	25.50	28.07	25.24
150	-	-	-	-	25.88	26.62	28.54	31.47	28.13
Mean	18.66	21.39	25.24	28.13	21.54	22.41	23.72	25.75	

Significance Level	LSD *for*					
	F_C	F_T	N	$F_C \times F_T$	$F_C \times N$	$F_T \times N$
0.01	0.77	0.77	0.77	0.96	0.96	0.96
0.05	0.40	0.40	0.40	0.62	0.62	0.62

Tablo H-3 Mean values showing 3-variable interaction effect among feed composition, feed rate, and trommel speed on screening inaccuracy of the trommel of 4.25-mm apertures

Feed Rate (F_T) kg/h	Mean Screening Inaccuracy, % — Feed Composition (F_C), (-)															
	0.150				0.325				0.500				0.675			
	Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min			
	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	32.75	33.47	35.90	36.80	19.42	20.12	22.20	24.98	10.93	10.60	11.92	13.05	4.75	4.55	5.33	7.88
90	33.22	33.92	34.07	37.53	23.30	24.67	25.63	27.45	14.77	15.25	16.55	18.42	4.82	4.67	6.30	8.70
120	34.45	36.70	41.87	43.72	26.63	28.25	29.32	31.07	15.75	16.60	18.92	21.62	8.85	9.27	10.62	12.62
150	33.82	36.30	41.30	49.52	30.38	32.07	32.12	33.47	18.87	19.38	21.92	23.38	10.47	11.78	13.47	15.05

Significance Level	LSD *for* $F_C \times F_T \times N$
0.01	1.77
0.05	1.22

Table H-4 Mean values showing 3-variable interaction effect among feed composition, feed rate, and trommel speed on screening inaccuracy of the trommel of 4.75-mm apertures

Feed Rate (F_T) kg/h	Mean Screening Inaccuracy, % — Feed Composition (F_C), (-)															
	0.150				0.325				0.500				0.675			
	Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min				Trommel Speed (N), r/min			
	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
60	32.77	33.85	33.68	34.83	21.37	22.30	22.92	23.80	10.83	13.47	14.13	15.55	3.87	3.78	5.23	6.23
90	32.97	34.87	35.37	37.08	25.10	25.02	26.58	27.95	16.72	17.50	18.62	20.15	4.52	4.70	6.88	8.27
120	37.77	38.13	40.67	45.20	26.68	27.50	28.67	30.43	21.43	22.13	22.38	23.77	7.07	8.78	10.28	12.87
150	39.35	40.82	45.63	50.17	31.67	32.27	33.38	37.23	21.92	22.32	23.27	25.37	10.60	11.07	11.87	13.12

Significance Level	LSD *for* $F_C \times F_T \times N$
0.01	1.68
0.05	1.16

Table H-5 Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, and trommel speed, on clogging index of the trommel of 4.25-mm apertures

Feed Composition (F_C) (-)	Mean Clogging Index, %								
	Feed Rate (F_T), kg/h				Trommel Speed (N), r/min				Mean
	60	90	120	150	10	15	20	25	
0.150	0.133	0.107	0.113	0.102	0.130	0.098	0.108	0.119	0.114
0.325	0.111	0.099	0.131	0.129	0.108	0.122	0.125	0.115	0.118
0.500	0.090	0.062	0.123	0.102	0.091	0.082	0.109	0.094	0.094
0.675	0.090	0.100	0.107	0.134	0.112	0.104	0.104	0.111	0.108
Mean	0.106	0.092	0.119	0.117	-	-	-	-	-

LSD for	Significance Level 0.01	0.05
F_C	0.016	0.008
F_T	0.016	0.008
$F_C \times F_T$	0.019	0.013
$F_C \times N$	0.019	0.013

Table H-6 Mean values showing main and 2-variable-interaction effects, among feed composition, feed rate, and trommel speed, on clogging index of the trommel of 4.75-mm apertures

Feed Composition (F_C) (-)	Mean Clogging Index, %				
	Trommel Speed (N), r/min				Mean
	10	15	20	25	
0.150	0.095	0.123	0.120	0.140	0.119
0.325	0.092	0.088	0.129	0.093	0.101
0.500	0.117	0.100	0.105	0.087	0.102
0.675	0.101	0.105	0.112	0.078	0.099
Feed Rate (F_T), kg/h					
60	-	-	-	-	0.092
90	-	-	-	-	0.101
120	-	-	-	-	0.109
150	-	-	-	-	0.120
Mean	0.101	0.104	0.117	0.100	-

LSD *for*	Significance Level 0.01	0.05
F_C	0.016	0.008
F_T	0.016	0.008
N	0.016	0.008
$F_C \times N$	0.020	0.013

Cost analysis of size classifying black pepper in a hexagonal trommel

The cost of size classifying black pepper in a hexagonal trommel was determined based on the following.

Initial cost of one trommel unit = Rs 15000-00
(*including prime mover and power transmission system*)

Salvage value = Rs 1500-00

Expected life = 10 years

Expected no. of working hours = 1500 h/year

Rate of interest per annum on capital = 15 %

No. of operators = 1

Daily wages of operator = Rs 250-00

System energy requirement/hour = 0.248 kW
(*at the maximum energy consumption of the power supply system*)

Cost of electricity = Rs 5-65 /kWh

Trommel capacity = 90 kg/h

Accordingly, the cost of screening is as given below.

(a) Fixed cost

Depreciation/hour $= \frac{15000 - 1500}{10 \times 1500}$ = Rs 0.90

Interest/hour $= \frac{(15000 + 1500) \times 15}{2 \times 1500 \times 100}$ = Rs 0.83

Housing cost/hour $= \frac{15000 \times 1}{1500}$ = Rs 0.10

(b) Operating cost

Cost of energy/h $= 0.248 \times 5.65$ = Rs 1.40

Repair and maintenance cost/hour $= \frac{15000 \times 5}{1500 \times 100}$ = Rs 0.50

Operator's wages/hour $= \frac{250}{8}$ = Rs 31.25

Therefore, total cost of screening/hour = Rs 35.00

And, unit cost of screening @ 90 kg/h = **Rs 0.40/kg**

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