ABSTRACT

Higher energy consumption and storage loss beyond permissible limit are the two most important problems in Indian potato cold stores, which have been hindering with the further growth of this industry. The problems of energy consumption and storage losses are interrelated in nature and have direct relation with the intricacy of the coupled transport phenomena of heat, mass and momentum transfer in bulk-stored potatoes. The heat and mass transfer processes within the bags of potato in a stack depend on product properties, and operating as well as geometric parameters of the cold store. The most important of these include, the rate of metabolic heat generation, porosity of the bulk medium, size and shape of the tuber, resistance of the product skin in preventing moisture loss, airflow pattern, temperature as well as relative humidity of the storage air used as the cooling medium, stack dimensions, location of cooling coils and ceiling fans, layout of the store, etc. All the above-mentioned parameters influence the mechanism of heat and mass transfer in the storage facility, which ultimately affect the temperature of the packed product and humidity around the product. Therefore, an in-depth analysis of the relative importance of these parameters on the mechanism of transport phenomena within the bulk-stored potatoes in a cold store will help to overcome the problems of higher energy consumption and storage losses beyond permissible limit.

There are numerous studies available in the literature on the aspect of modeling of transport phenomena in the bulk–stored product employing various numerical techniques and covering wide range of agricultural produce as well as storage conditions. It has also been noticed that most of the research work on the aspect of cold store technology was done outside India. Therefore, the results of these research works reflected a storage system that deviated from the technology prevailing in Indian potato cold store in principle. However, to-date not even a single mathematical model was developed to get the insight of the mechanism of heat and mass transfer in bulk-stored product kept in an Indian potato cold store system. This emphasized on an immediate need to develop modeling strategies in context with a typical Indian potato cold store system. Therefore, a CFD model was developed in the present study to simulate the heat and mass transfer processes in a single stack of potato. The model was also verified through the experimentation in a

commercial potato cold store. The validated CFD model was used to predict the effect of product properties, operating parameters, stack dimensions and stacking arrangements on the cool-down characteristics of the potatoes in the stack. The same model was also employed to predict the sensible product-cooling load under different loading patterns and cooling rates. The CFD modeling technique was successfully applied to model the airflow, heat and mass transfer in a full-scale commercial potato cold store during the steady-state condition only. The model identified some lacunae in the existing design of the cold store, which were responsible for non-uniform distribution of product temperature and moisture loss in the storage chamber due to poor air circulation. Therefore, some design improvements were attempted in the present study to improve the air circulation as well as heat transfer and hence in reducing the moisture loss during the long-term storage.

A commercial stack of bagged potatoes was modeled as a two-dimensional heat and mass generating porous medium with permeable boundaries subjected to cooling under natural convection. The boundary conditions at the surfaces of the single stack were similar to those existing in the whole cold store. However, to get a view of the airflow pattern, temperature profile and moisture loss in the whole storage chamber, a two-dimensional model under steady-state was considered in the present study. The family of Navier-Stoke's equations along with energy and water vapor transport equations was solved using the finite volume technique. The computations were performed with the help of a commercially available code Fluent v. 6.1.18 on a Pentium-IV PC having 1 GB RAM. Second order upwind scheme was chosen to discretize the momentum, energy and water vapor transport equations. However, the discretization in time was first order implicit. PISO algorithm was selected for pressure-velocity coupling. The solution was updated to the next time step when the scaled residuals for continuity, momentum, energy and water vapor transport equations were less than 10^{-3}, 10^{-3}, 10^{-6} and 10^{-5}, respectively. Sufficiently small time step of 1 second was chosen in the beginning to achieve the convergence within 12 - 20 iterations. Later on, the time step was increased gradually up to 1 h as the cooling proceeded.

In a stack of potatoes, the contours of temperature, relative humidity, rate of moisture loss and total moisture maintained non-symmetry about the horizontal and vertical axes. The zone of maximum temperature and moisture loss was observed in the upper central zone of the stack due to low relative humidity therein. The temperature at the surface of stack followed closely the surrounding air temperature in horizontal direction. Also, at a particular instant of time, the temperature of the product at the bottom of the stack was found to be higher than the side surfaces of the stack. The heat and mass exchange between the product and air occurred at a very fast rate during the first four days of cooling.

It was found that increasing the porosity of the bulk medium reduced the temperature and moisture loss during the cooling period. The rate of moisture loss and relative humidity (*RH*) in the stack at steady state did not show significant changes with the porosity of the bulk medium. The metabolic heat of respiration increased the temperature of the product and moisture loss during the transient cooling period and steady-state. Moisture loss and *RH* in the stack increased with decreasing the resistance of the product skin towards mass transfer. The cool-down time was decreased with the increase in bulk medium porosity and metabolic heat of respiration. As the storage air temperature increased the temperature of the product and moisture loss during the transient cooling and steady-state also increased. It was also observed that in comparison to storage air temperature, the *RH* of the storage air had more influence on the moisture loss from the product. The moisture loss decreased and *RH* in the stack increased with increasing the *RH* of the storage air.

The height of the stack had maximum influence on average product temperature, moisture loss and cool-down time in comparison to width and volume of the stack. It was found that horizontal and vertical gaps of 0.05 – 0.1 m were sufficient to improve the heat transfer in the stack. Any additional gap would result in wastage of precious storage space. The total moisture loss as well as rate of moisture loss at steady-state decreased with increasing aspect ratio and horizontal as well as vertical gaps, while these were found to increase with increasing the height and volume of the stack. The average sensible product-cooling load increased with increasing aspect ratio and horizontal as well as vertical gaps, while it decreased with increasing the height and volume of the stack. The width of the stack did not show any significant effect on moisture loss and product-cooling load. The product kept in a stack having rectangular cross-section would incur low moisture loss in comparison to a squared shaped one, though, higher cooling capacity would be required for the former case. Comparing the total moisture loss during the 8 months of storage in the stacks of different dimensions, it was found that a maximum of about 41 % reduction in moisture loss could be achieved just by changing the stack dimensions and stacking arrangement, of course, the capacity of the refrigeration system should be increased accordingly.

The loading rate and temperature of the storage air during loading period showed considerable effect on the temporal variation of sensible product-cooling load. Under the prevalent pattern of storage air temperature, linearly decreasing loading rate would give minimum peak sensible product-cooling load while corresponding to linearly decreasing storage air temperature, constant loading rate showed minimum peak sensible product-cooling load. In order to accommodate the actual loading pattern, the loading of the potato should be done at a constant higher storage air temperature.

The output of the model for whole cold store indicated that the present arrangement of cooling coils and ceiling fans in the cold store was unable to circulate the cold air throughout the storage chamber uniformly, which resulted in wide variations in temperature and moisture loss within the stacks. The present modeling strategy was used to optimize the location of cooling coils and ceiling fan assembly with a view to obtain the uniform air distribution and hence, uniform product temperature as well as moisture loss throughout the storage chamber. It was found that adding an obstruction between the ceiling fan and left sidewall of the storage chamber significantly improved the air circulation and reduced the product temperature and moisture loss.

The simulation model was able to predict very well the pattern of temperature during the cool-down period at all the locations taken in this study; though, the magnitude of errors deviated from location to location in the stack. The overall average temperature differences between the experimental and simulated data for the cooling period of about one month at all the designated points were found to be 1.3 ± 1 °C and 1.2 ± 1 °C in the temperature range of the product of 3.5 – 26.4 °C and of 3.4 – 26.9 °C for two different chambers. The overall average errors between the experimental and simulated total moisture loss for the bags in both the chambers were 8.03 ± 2.1 % and 10.5 ± 2.7 %, respectively.

Chapter-1

INTRODUCTION

The objectives of storage of potato are mainly to ensure future supply, further processing and maintenance of seed reserve. It allows better use of processing capacity, better tuning of production and consumption and supply of better quality of seed potatoes. Potato, being an arable product, belongs to the category of semi-perishable goods, having a high moisture content of about 80 %. For the preservation of potato in its whole form for long-term storage, cold store is the only plausible method. Systems used for storage of potato all over the world are characterized in Fig. 1.1. They are underground storage, storage without buildings and storage in buildings. Limiting to long-term storage of potato at low temperature, there are three common methods for storage of potato in commercial cold stores, namely, bulk storage, storage in crates and storage in sacks, *i.e.* in gunny bags (Ooster, 1999). In the Indian potato cold store, the third method of storage is employed, wherein the potatoes are packed in gunny bags and arranged in the form of a stack (Anonymous, 1964).

Low storage air temperature, high relative humidity and control of air composition are the main conservation factors for storage of agricultural produce. The life of agricultural produce during storage in cold store depends on many factors such as temperature of the product, extent of water loss, surrounding atmospheric conditions, etc. (Chourasia and Goswami, 2006 a). All of these factors are influenced by the temperature and moisture content of the air in the storage chamber with the airflow governing the uniformity of the conditions. To guarantee a top quality product, therefore, these storage conditions must be well controlled, which require a knowledge of heat and mass transfer processes and their dependency on fluid flow within the bulk medium. The proper storage environment for potato may be defined as the environment which will promote the most rapid healing of bruises and cuts, reduce rot penetration to a minimum, allow the least mass and other storage losses to occur and reduce to a minimum the deleterious quality changes that might occur during cold store (ASHRAE, 1990).