ABSTRACT

A model has been suggested for combustion of coal in fluidized beds having large carbon concentration and it has been critically analysed with suitable experiments. The theoretical and experimental results are in good agreement. Experimental data were also collected for combustion in partially fluidized beds in which the bed was initially fixed and later got fluidized with progress of combustion. The investigation was extended to study oscillating bed combustion in which intermittent long puffs of air were superimposed on the main air stream to improve the performance of partially fluidized bed combustion.

SYNOPSIS

Fluidized bed coal combustion is a novel means of burning coal for power generation. Small coal particles are injected into a fluidized bed material and combustion of fixed carbon and volatile matter take place in the bed. Considerable amount of heat generated is extracted by means of cold water circulated in immersed tubes, and transfer of heat from bed to tube is mainly by conduction and radiation.

The attractive aspects of this method of burning coal are uniform low bed temperature, high heat transfer rate, insensitivity to coal grade and effective pollution control. Although these benefits have been broadly realised at smaller and pilot scale plants in many countries, still there is some sort of reluctance to adopt this process for new and large scale installations or for conversion of existing power plants. Present designs do not prove to be so attractive, when overall plant efficiencies and ultimate power cost estimates are considered. A significant portion of power generated is consumed in pumping air and fuel into the system. Fluidizing a heavy bed material also consumes considerable amount of energy. Large quantity of bed material is required for continuous replacement as their size get constantly reduced due to attrition and abrasion at higher velocities and temperatures. Selection, procurement, preparation and disposal of such bed material after use are still pertinent problems to be solved.

Entrainment of fuel particles and bed material can be solved to a great extent by use of suitable filters and collectors and also by recycling in separate smaller burn up cells for complete combustion. The effective pollution control capabilities are more fascinating for countries like the U.S.A. where high sulphur content coals are available. To circumvent some of these problems efforts are being made on "Pressurized Fluidized Bed Coal Combustion" and also to use large coal pieces in shallow fluidized beds.

The ignifluid combustion is yet another parallel effort in burning coal for steam generation. This process does not make use of any bed material, and overcomes all problems associated with inert bed material. Small particles of coal bed are fluidized and burnt. Partial combustion takes place in the bed and complete combustion is achieved by secondary air injection. Ignifluid combustion was originally developed in the early sixties by Albert Godel. He maintained air velocities between 10 to 15 m/sec and bed temperatures between 1200°C to 1400°C. He found that small clinkers appeared throughout the bed at these high temperatures and remained fluidized and grew in size without any risk. Air was introduced into the bed through an escalating grate. The edges of the grate were relatively stagnant and the clinkers were removed from the combustion chamber as it revolved.

Ash agglomeration has been a major hurdle in the progress of ignifluid combustion process. Heat extraction from bed through immersed tubes is not possible as the formation of clinker would spoil the tube surface. Pollution controls are not possible as in the previous case wherein suitable bed material is used for removal of sulphur, and so high sulphur content coals can not be used. Ignifluid combustion remain only in the preliminary stage even though few ignifluid boilers without any immersed tubes have been developed. No systematic research work has been done so far aiming at modelling this combustion process, and no operational data have been published.

The problem of ash agglomeration in such fluidized combustion process are due to two reasons.

(1) Due to caking property of coal :

At lower temperature levels coal particles become sticky if the coal is of caking variety then agglomeration of coal particles occurs. This results in improper fluidization and combustion occurs as in the case of fixed beds.

(2) High bed temperature :

The other reason for ash agglomeration is due to high temperature of bed due to improper cooling inspite of better fluidization achieved. If the bed temperature can be maintained below ash fushion temperature by providing proper cooling arrangements, and if the bed is well fluidized without leaving any small pockets of stagnation even at lower velocities, the problem of ash agglomeration can be completely eliminated.

This is achieved in the present investigation by using a non-caking variety of coal and with bed cooling.

Lignite which is about 30% of world's solid fuel production is a non-caking coal and this and other weakly caking bituminuous varieties can be used with some pre-treatment in ignifluid combustion. Such coals can also be used with small amount of bed material without any pretreatment. It is to be remembered that caking and highly caking varieties are very much needed for metallurgical purposes. Sulphur content of coal available in this country is low and so positive pollution controls are not very essential. Under these circumstances, advocating coal combustion with bed material even for non-caking or weakly caking coals is unnecessary.

The fluidized bed coal combustion refers to the combustion of coal in a fluidized bed material. The concentration of coal in the bed is very low. The fluidized coal bed combustion indicates the combustion of coal in the fluidized state without any bed material or with small quantity of bed material, where the concentration of carbon in bed is very large. The present work on fluidized coal bed combustion retains the advantages of faster rate of reaction and heat transfer.

Avedesian and Davidson model is a significant contribution which explains the mechanism of combustion of coal particles in an inert fluidized bed. Their model leads to an expression for burnout time of char particles assuming perfect mixing in the fluidized combustor. The model is confirmed by a new experimental technique. Coal particles of one to five grams were dropped into an inert fluidized bed in quartz combustor which was maintained hot by external electrical heating. The burnout time was noted from the time at which particles were dropped from above and the time at which the bright burning particles disappeared in the bed. Avedesian and Davidson felt that a portion of their expression would be applicable for cases where there is large concentration of coal and regretted for nonavailability of data for testing. The model suggested by them does not take into account the volatile matter of coal and is more appropriate for low carbon concentration beds. The data has been collected to test the theory by a table model experimentation. Variations are bound to be there in larger plants. The single particle combustion model suggested by them was tested by Basu et al by inhibiting carbon monoxide to carbon dioxide reaction and by using an infra red continuous recorder. The batch operation model suggested by Avedesian and Davidson is extended for continuous operation by Campbell and Davidson.

The physical situation of the problems under consideration in batch operation are illustrated in Figs. 1.1, 1.2 and 1.3 The curves show the relationship between pressure drop and superficial air velocity with the reduction of particle size and bed weight as combustion progresses. The start of fluidized combustion is denoted by the point X in Fig.1.1 and completion by Y. When it reaches the point Y, the particle size becomes so small that elutriation of the whole bed occurs. As the elutriated particles rise up, they get burnt up and the bed vanishes. During this set of experimentation the bed is in <u>fluidized stage</u> from beginning to end of combustion.

Fig. 1.2 describes the second set of experimentation starting at X as a fixed bed and ending at Y as a fluidized bed. The bed behaves as fixed for sometime and fluidized for the rest of the combustion time. Such a bed which behaves initially as a fixed bed and subsequently gets converted as a fluidized bed with the progress of combustion, has been termed as a partially fluidized bed.

Fig.1.3 refers to a combination of fluidized and partially fluidized combustion. Steady air flow as in partially fluidized bed is maintained and intermittent long puffs of air are superimposed through another by-pass line. This makes the bed expand and contract depending on the by-pass flow. Such a bed which continually expands and contracts due to this intermittent superimposed air flow has been termed as an oscillating bed.

A pilot scale plant was designed, fabricated and erected for experimentation of all these three parts. The diameter of the combustor is 30 cm with circumferential water cooling. Water was regulated by a gate valve and an overhead tank with continuous refilling by a centrifugal pump, which maintained a steady flow. For every hot run, on batch operation, water flow was reset, at a predetermined flow rate. Total height of the combustor is about 1.8 m. Elutriated particles were filtered by a cyclone separator from the burnt gases before it was exhausted into atmosphere and channeled to a separate container. The entire combustor assembly and the above container all mounted on a platform weighing balance. Flexible connections have been provided wherever necessary so that the balance can read at every instant, the amount of coal inside the combustor. Coal is fed through the charging door and the time for certain reduction in the balance reading is noted as combustion proceeds. Top ignition of the bed was done by spraying small quantity of kerosene and spreading few drenched waste cotton pieces on top of the bed and setting fire to it. Number of permanent holes with threaded plugs for closing them have been provided at different heights of the combustor. Through these holes temperature measuring probes are inserted and gas collections are made for analysis. Air flow rates are measured by orifice meters and pressure drops by 'U' tube manometers. Oscillating flow is introduced through a by-pass pipe line. A separate mechanism was fabricated to induce oscillating flow by opening and closing butterfly valve fixed inside the by-pass line. Frequency and amplitude of the long intermittant puffs of air in the by pass line were varied with the aid of this mechanism.

Part - I

Fluidized Coal Bed Combustion

On the assumption that oxygen to burning particles is available by molecular diffusion only a single coal particle model has been suggested. It is taken that carbon monoxide is the only product of combustion. Assuming piston flow in the fluidized combustor, i.e., uniform oxygen concentration across a horizontal plane and no mixing in the vertical direction, a bed model has been developed. The bed model considers heterogeneous reaction in the particulate phase only. Homogeneous reaction in the bubble phase has been neglected. Uniform bed temperature from entry to exit is assumed. Three distinct cases under different boundary conditions based on the second order differential equation of the bed model are discussed. Very large carbon concentration in the fluidized bed is one such case which is subjected to rigorous experimentation. The burnout time for fluidized coal bed combustion is derived from first principles and it is given by

$$t_c = \frac{\bar{M}}{12\, U A_r C_o \left(1 - e^{-x} + \frac{e^{-x}}{U_R}\right)}$$

where

t_c = Burnout time of carbon particle, sec

$\bar{M}$ = Mass of effective charge, kg

U = Superficial air velocity, cm/sec

A_r = Cross-sectional area of the combustor, cm^2

C_o = Concentration of O_2 at entry, kg Mol/m^3

X = Interphase transfer factor

U_R = U/U_o, velocity ratio

U_o = Minimum fluidizing velocity, cm/sec corresponding to $\bar{M}$.

The concentration of oxygen just above the bed is given by the following equation

$$C_{bH} = C_o e^{-x}$$

where C_{bH} = Concentration of oxygen above the bed.

The above equation is quite similar to a portion of Avedesian and Davidson's expression which they felt would suit for cases of very large carbon concentration.

Two minutes after top ignition of bed the air rate is increased in the main pipe line to the required level, which is always more than U_{oh}, the minimum fluidizing velocity under hot condition. Then the air flow rate is increased suddenly to just above U_{oc}, the minimum fluidizing velocity under cold condition and then stopped. This operation fluidizes the bed which is not only on the top surface, the rest of the bed being cold. This blow-hot and blow-cold operation mixes ignited particles in the bed and since the reactivity of the coal is high and U_{oh} is continuously maintained, the whole bed ignition takes place in one or two minutes. There are clear indications to show that the whole bed has been ignited and fluidized. When the bed temperature crosses roughly 400°C, the stop watch is started to mark the beginning of fluidized combustion. At burnout time the whole bed of very small burning particles rise up and vanish. The stop watch is then stopped. Rate of cooling water is adjusted and the average bed temperature has been maintained roughly at 800°C.

Since the burnout time has been noted roughly after

$400^{\circ}C$ of bed temperature the evolution of volatile matter takes place and it gets eliminated from the process of combustion. The mass of effective charge $\bar{M}$ and the corresponding U_o are calculated from the weight reduction versus time curves. Ash is not elutriated away and it is collected on the balance. A small proportionate correction made for ash collected on the balance gives at every instant the fixed carbon content in the combustor. Thus the process of calculation eliminates the ash content of coal also. The experimentation has been done on a pilot scale plant with one to three kg of coal for every run, which is more representative of the actual plants. Gas collections have been made from top of the bed at different intervals of time and analysed. Close agreement between the theory and experimented results have been found.

Part - II

Partially Fluidized Bed Combustion

The second series of experimentation have been done on the partially fluidized bed combustion. The start of combustion is only with the top bed ignition. Whole bed ignition is not done. Water rate has been adjusted to maintain the bed temperature at $800^{\circ}C$ to the possible extent. The indications of burnout time are not simultaneous as in the fluidized coal bed combustion. One or two minute differences have been noticed and for such cases the average has been taken as the burnout time. This work was attempted to interlink the fixed bed combustion and the fluidized bed combustion. The variations of pressure drop and temperature with time have also been noted. At lower velocities clinkering was more and in some cases the bed behaved as fixed bed from beginning to end.

Part - III

Oscillating Bed Combustion

Lighting up of the bed is done as in the second case. The bed starts as a partially fluidized bed, and is made fluidized with injection by long puffs of air through by-pass line. This is an attempt to reduce clinkering noticed at lower velocities as observed in Part II. Clinkering was here very much reduced, but carbon particle elutriation was a problem faced. The effect of increase in superimposed oscillating velocity and effect of its frequency have been studied.