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EFFECT OF BED TEMPERATURE, FUEL DENSITY AND PARTICLE SIZE ON HYDRODYNAMIC PARAMETERS OF A 10 MW FLUIDIZED BED COMBUSTION POWER PLANT USING RICE WASTE

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ABSTRACT

The design and operation of boilers using rice waste present a number of challenges. The overall capacity and efficiency of the boiler are strongly dependent on the fuel, and the supplier has to be able to guarantee the capacity and efficiency within the whole range of the fuel mixture being burned. It is well known that the exit gas composition is strongly dependent on the fuel. Bed temperature, fuel density and particle size significantly affect the hydrodynamic properties of a fluidized bed combustor. The effect of bed temperature, fuel density, particle size on exit gas composition and other hydrodynamic parameters of 10 MW power plant is discussed in this paper, and a heat balance sheet for the 10 MW fluidized bed boiler based on rice waste is prepared. Heat release in the fluidized bed region is also calculated and the efficiency of fluidized bed boiler is found.

1.0 INTRODUCTION

Energy consumption in the world in the form of petroleum-based fuels has increased several fold during the last 20 years. Fast depleting stocks of fossil fuel and steep increases in their prices may lead to an energy crisis in the future. With declining reserves and fluctuating prices of fossil fuels, the search for an alternative renewable raw material to replace petroleum has intensified. Rice waste is an agro residue which is found in regions where the demand for energy exists. Rice waste is primarily comprised of rice straw, rice husk and rice bran. Fluidized bed combustion a technology, which produces energy efficiently with a wide range of fuels, at low temperature and at isothermal conditions. Due to these reasons a number of commercial fluidized bed power plants of 10-20 MW capacities based on rice husk/rice straw have been installed in the last two decades for power generation.

Rice husk and rice straw are the waste materials which are incinerated in a fluidized bed combustor (FBC) in Punjab (India) and adjoining areas. Due to high collection costs, feeding problems and agglomeration problems, the rice straw is not incinerated in most commercial fluidized bed combustors in its present form. Rice husk can be easily bought from commercial rice mill owners, and is the main fuel used in commercial atmospheric fluidized bed combustors based on rice husk/rice straw. A three-phase mathematical model for exit gas composition and solid population balance (2) (4) for shrinking particles in an atmospheric bubbling fluidized bed combustor using rice-husk was developed in previous studies. The main aim of this paper is to study the effects of fuel density, bed temperature and particle size on hydrodynamic features of the plant and to calculate the various heat transfer effedcts in the 10 MW power plant situated at Jalkheri, Patiala, Punjab, India. Figure 1.1 shows the schematic diagram of the boiler, and Figure 1.2 shows the layout of the biomass based plant at Jalkheri for which the study and model were developed.

Ravi Inder singh et al. (1) conducted a study of an atmospheric bubbling fluidized bed combustor for a 10 MW power plant based on rice husk. In his paper an environmental assessment, an exit gas composition model, an agglomeration problem and a model for a solids population balance for the 10 MW power plant at Jalkheri, Punjab, India using rice husk is discussed. Goo al (2) studied the effects of temperature and particle size on minimum fluidization and transport velocities in a dual fluidized bed. They found that the minimum fluidization velocity decreased with temperature due to the increase of gas viscosity. The transport velocity increased with increasing temperature. They proposed correlations in terms of Reynolds and Archimedes numbers.

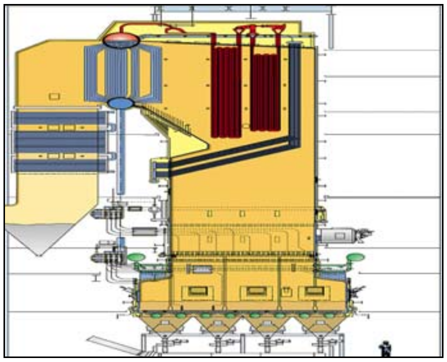


Figure 1.1 Schematic diagram of Boiler

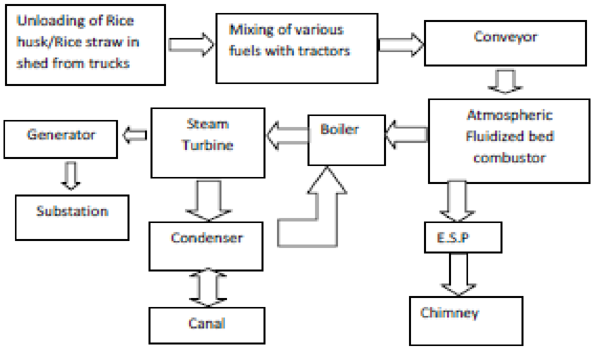


Figure 1.2: Schematic diagram of 10 MW Jalkheri power plant

2.0 MODEL FORMULATION

A mathematical model was developed to calculate the exit gas composition and solids population balance for a 10 MW FBC power plant suitable for biomass particularly rice husk. The model was validated by collecting data from the 10 MW commercial FBC plant based on biomass (1). The model was based on the three-phase theory of fluidization and single film theory of carbon combustion. It was based on the assumption that essentially the $C + O_2 = CO_2$ reaction is taking place in the combustor. It was assumed that the fluidized bed consists of a number of stages and the height of each stage was equivalent to the average bubble diameter. Each stage consisted of the bubble, cloud, and emulsion phases. Bubbles were solids free and gas in bubbles were in plug flow, bubbles and the cloud-wake rise at the same velocity. In each stage the emulsion and cloud-wake phases were back mixed. The voidage in both these phases were the same at incipient condition. The assumption that combustion does not involve a change in number of moles and that char and volatiles burn at the same rate throughout the bed was assumed. The main features of these models were physical chemical processes occurring in a fluidized bed combustor based on rice husk, oxygen mass balance for exit gas composition and a solid population balance. The details of the models can be obtained from references (1) and (3). A brief description of model is given below.

Oxygen balance around stage 'n' for the bubble phase

Oxygen in by convection-Oxygen out by convection -Oxygen transfer to cloud-wake = 0
It is represented symbolically as;

$$U_b C_{b_{n-1}} - U_b C_{b_n} - (K_{bc})_b \varepsilon_b \int_{Z_{n-1}}^{Z_n} (C_b - C_{cw_n}) dZ \qquad (2.1)$$

Oxygen balance around stage 'n' for bubble-cloud wake phase

|Oxygen in by convection | – |Oxygen coming from bubble phase by transfer | – | Oxygen going out from cloud –wake to emulsion by transfer | – |Oxygen out from cloud-wake by convection | – | Oxygen consumed in cloud-wake phase| = 0
Symbolically, this can be represented as:

$$U_{cw}C_{cw_{n-1}} + (K_{bc})_b \varepsilon_b \int_{Z_{n-1}}^{Z_n} (C_b - C_{cw_n})dZ + K_{ce}C_{e_n} - (U_{cw} + K_{cw} + K_{ce})C_{cw_n} \tag{2.2}$$

Where

$$K_{ce} = (K_{ce})_b \varepsilon_b \Delta Z \text{ , } K_{cw} = (K)(f_{cw})(\varepsilon_b)(\Delta Z) \text{ and } \Delta Z = Z_n - Z_{n-1} = D_b \tag{2.3}$$

Oxygen balance around stage 'n' for the emulsion phase

|Oxygen in by convection| – |Oxygen out by convection | + |Oxygen transfer from cloud-wake phase | = |Oxygen consumed by Combustion reaction |

Symbolically, this can be represented as:

$$U_{mf}C_{e_{n-1}} + (K_{ce})(C_{cw_n}) - (U_{mf} + K_e + K_{ce})C_{e_n} = 0 \tag{2.4}$$

Where $K_e = K[1-\varepsilon_b(1+f_{cw})]\Delta Z$ and $K_{ce} = (K_{ce})\varepsilon_b \Delta Z$ (2.5)

The the oxygen balance over a height (dZ) in the bubble phase is written as:

$$U_bC_b - U_b(C_b + dC_b) - (K_{bc})_b \varepsilon_b (C_b - C_{cw_n})dZ = 0 \tag{2.6}$$

Rearranging and integrating the above equation, we get

$$C_b - C_{cw_n} = (C_{b_{n-1}} - C_{cw_n})\exp[\{-(K_{bc})_b \varepsilon_b (Z - Z_{n-1})\}/U_b] \tag{2.7}$$

At the bottom of the bed (n=0), the concentration of oxygen fed to each phase is the same as that of the incoming feed oxygen. Hence, the boundary conditions are:

At n=0, $C_{b_n} = C_{cw_n} = C_{e_n} = C_0$ (2.8)

Equations 2.1-2.7, together with the boundary conditions in equation 2.8, make up a complete mathematical description of the system. Details could be referred from (1) and (3). The average gas composition leaving the n^{th} stage, i.e at the top of the bed is:

Oxygen $C_{avg} = (U_bC_{b_n} + U_{cw}C_{cw_n} + U_{mf}C_{e_n})/U_0$ (2.12)

Carbon dioxide $CO_2 = C_0 - C_{avg}$ (2.13)

Nitrogen $N_2 = (0.79/22,400)(273/T_b) + [XN(1-XW)]/28.U_0.A_t$ (2.14)

3.0 HEAT BALANCE CALCULATIONS IN 10 MW PLANT

The amount of heat entering the bed and various losses have been calculated. Finally thermal efficiency is calculated and the results shown in Table 4.3 and Figure 4.14.

3.1 Heat added to fluidized bed combustor

Q_{ha}= mass of fuel * Calorific value of rice waste (3.1)

3.2 Heat lost to flue gases: The flue gases contain dry products of combustion as well as the steam generated due to combustion of hydrogen in the fuel.

$Q_{fg} = m_g * C_{pg} * (T_g - T_a)$ (3.2)

3.3. Heat carried away by the steam from flue gases

$Q_{sg} = m_{s1} (hs_1 - h_{f1})$ (3.3)

3.4 Heat lost due to incomplete combustion

Heat lost due to incomplete combustion (6) of carbon per kg of fuel

Q_{ic}= [CO × C / CO_2 + CO] × 23680 KJ/kg of fuel (3.4)

3.5 Heat lost due to unburnt fuel

$Q_{ub} = m_{f1} \times$ C.V (3.5)

3.6 Convention and Radiation losses

The loss of heat due to convection and radiation losses

Q_{cr}= Heat released per kg of fuel – ($Q_g + Q_s + Q_{ic} + Q_{ub}$) (3.6)

3.7 Equivalent evaporation (m_e) = $m_a * (h - h_{f1}) / h_{fg}$ (3.7)

3.8 Boiler efficiency

$\eta_b = m_a * (h - h_{f1})$ / C.V (3.8)

3.9 Average Heat transfer Coefficient

The overall bed heat transfer coefficient is given by

$$h_{\alpha} = \text{Heat Transfer flux} / A.\ \Delta t \tag{3.9}$$

More details could be found in the work of (6).

4.0 RESULTS AND DISCUSSIONS

The input data required for the exit gas model and solid population model (1) was taken from a 10 MW FBC plant at Jalkheri (Jalkheri Power Pvt. Limited, Fatehgarh Sahib, Punjab, India). The plant uses the rice husk (80%) and rice straw (20%) as feed stock. The average size of rice husk particle ranges from 0.25 to 0.625 cm. At one time the size of the rice husk particles was uniform. Bed temperature ranged from 925 K to 1125 K. The density of fuel varied from 0.09 to 1.2 g/cm^3 as fuel consists of rice husk and rice straw. The proximate and ultimate analyses of rice husk were done at different times and the result of one such sample is given in Table 4.1. The results of these analysis, along with the other physical-chemical parameters taken from plant were the input parameters to the model in Section 3.0 and (1). Fuel density,

Table 4.1 Proximate and ultimate analysis of rice waste sample

Proximate analysis (Rice husk)		Ultimate analysis (Rice husk)	
Volatile	58.03	C	38.9
Fixed Carbon	16.65	H	5.1
Ash	17.82	S	0.12
Moisture	7.5	O	37.9
		N	2.17

Table 4.2 Physico chemical parameters of Plant

Type of fuel used (at time of study)	Rice husk and rice straw	Area of fluidized bed	391000 cm^2
Feed rate of fuel	3200 g/s	Type of distributor	Nozzle type tuyre
Feed rate of water	11110 g/s	Total no. of holes in distributor	22500
Air flow rate	20×10^6 cm^3/s	Specific fuel consumption	1300 g of fuel /unit generation
Rate of steam generation	10830 g/s	Bed Voidage	0.48
Main steam temperature	400^{o}C	Bed height at minimum fluidization	48 cm
Combustion efficiency	82% (Designed Value)	Boiler capacity	50 T/hr equivalent to 13888.88 kg/s

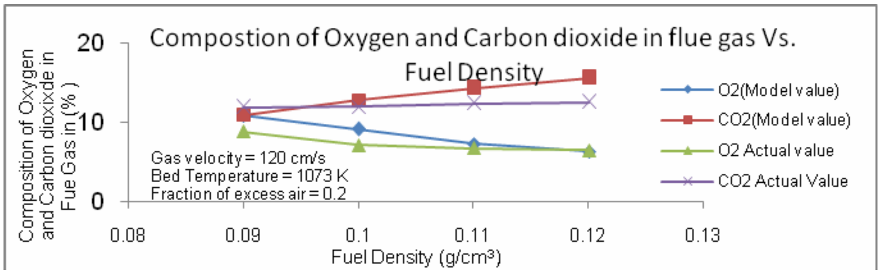


Figure 4.1 Composition of oxygen and carbon dioxide in flue gas vs. fuel density

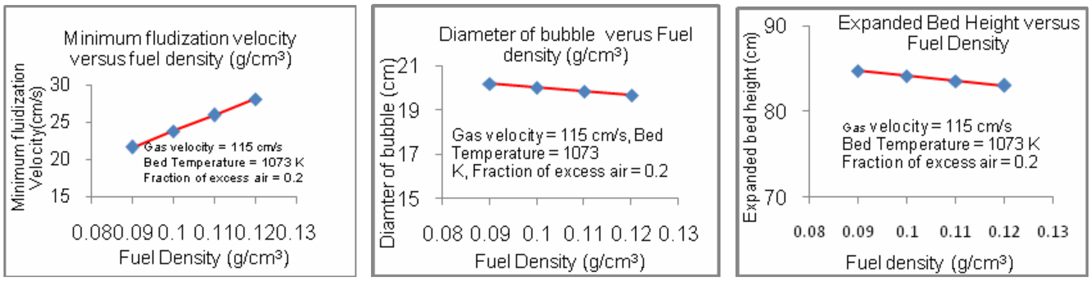


Figure 4.2, 4.3 and 4.4 Minimum fluidization velocity, bubble diameter and expanded bed height vs. fuel density

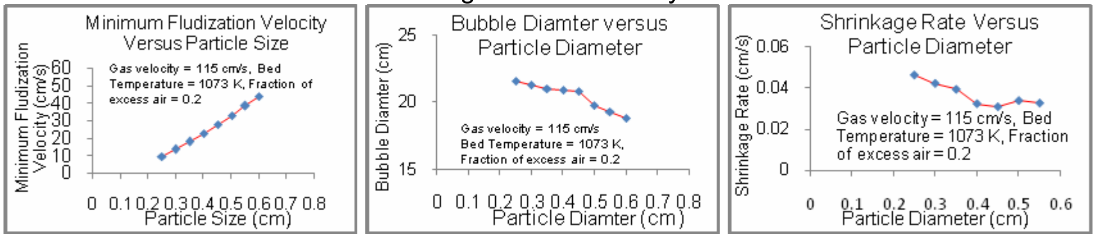
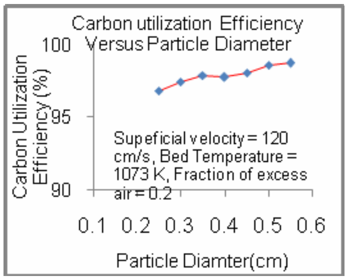


Figure 4.5, 4.6 and 4.7 Minimum fluidization velocity, bubble diameter and shrinkage rate vs. Particle size



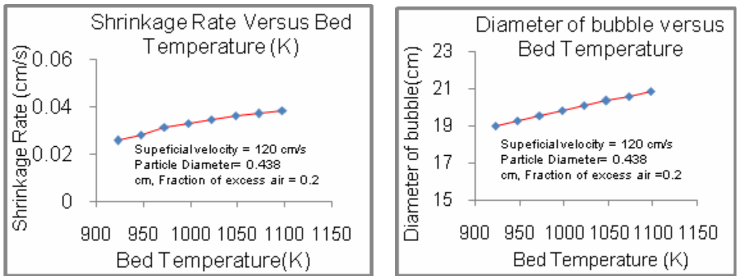
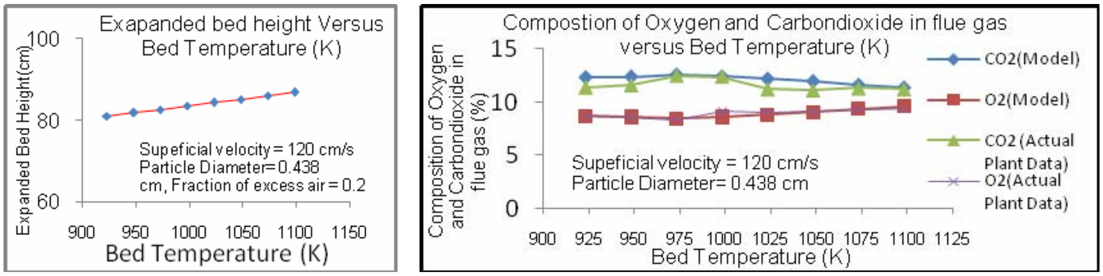


Figure 4.8 Carbon utilization efficiency Vs. Bed temperature

Figure 4.9, 4.10 Shrinkage rate and diameter of bubble vs. Bed temperature



Figures 4.11 and 4.12 Expanded bed height and the composition of oxygen and carbon dioxide in the flue gas vs. Bed Temperature

bed temperature and particle size are the important parameters which decide the various hydrodynamic properties of FBCs. The output of both models resulted in hydrodynamic parameters, exit gas composition, carbon utilization efficiency etc. of the FBC situated at Jalkheri. The data given in table 4.2 were used to prepare the heat balance sheet for the Jalkheri boiler, and to calculate the actual thermal efficiency of the boiler at the time of operation. The variation of oxygen and carbon dioxide in the flue gas with fuel density is shown in Figure 4.1. The model values closely match the actual plant data. The value of carbon dioxide increases and oxygen decreases. It is due to the fact that the combustion of dense fuel is more proper than less dense fuel. The oxygen supplied to the dense fuel is more than less dense fuel. The trend of U_{mf} is shown in Figure 4.2. U_{mf} increases with increasing density and is directly proportional to fuel density.

The trend of bubble diameter with fuel density is shown in Figure 4.3. Bubble diameter decreased with increasing fuel density because the bubble diameter is dependent on the difference between superficial velocity and U_{mf}. As U_{mf} increases, it causes the bubble diameter to decrease. The trend of expanded bed height with fuel density is shown in Figure 4.4 The expanded bed height increases is due to increase of bubble diameter.

The trend of minimum fluidization velocity with particle size is shown in Figure 4.5. It increases with increasing particle diameter. The bubble diameter and shrinkage rate with particle diameter are shown in Figure 4.6 4.7. Both decrease with increasing particle diameter as these are inversely proportional to particle diameter and due to the fact that U_{mf} increases as particle size increases causing the increase of bubble diameter. Carbon utilization efficiency increases with increasing particle diameter because large particles stay in the fluidized bed longer than smaller particles.

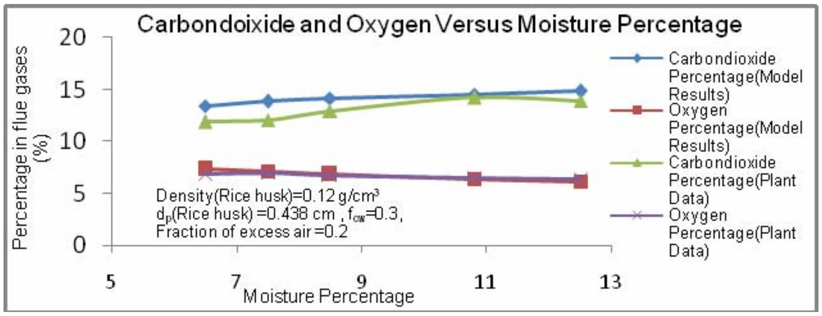


Figure 4.13 Variation of percentage of gases in flue gas with moisture

Shrinkage rate, bubble diameter and expanded bed height with bed temperature are shown in Figures 4.9, 4.10 and 4.11. Bubble diameter is dependent on U_{mf} which is further dependent on gas viscosity. Gas viscosity decreases with increasing bed temperature. This causes the minimum fluidization velocity to decrease which further increases the bubble diameter. Bubble diameter causes the expanded bed height to increase. Bed temperature causes reaction rates to increase which causes the shrinkage rate to increase.

Table 4.3 Heat balance sheet of Jalkheri Power Plant

Notation	Description	Calculated Value	Notation	Description	Calculated Value
Q_{ha}	Heat added to fluidized bed	48 MJ	Q_{ub}	Heat lost due to un burnt fuel	0.125 MJ
Q_{fg}	Heat lost to flue gases	0.62 MJ	Q_{cr}	Convention , Radiation and other losses	13.31 MJ
Q_{sg}	Heat gained by steam	33.93 MJ	m_e	Equivalent evaporation	4.697 kg/kg of fuel
Q_{ic}	Heat lost due to incomplete combustion	0.015 MJ	η_b	Calculated value	70.68 %

The variation of oxygen and carbon dioxide in flue gas with bed temperature is shown in Figure 4.12. The model values are completely in accordance with plant results as shown in the figure. Carbon dioxide increases up to 975 K and thereafter decreases. After 975 K the problem of agglomeration predominates and that causes non-uniform combustion in the fluidized bed, which causes the carbon dioxide values to decrease and oxygen to increase.

The moisture in rice husk varies throughout the year. The effect of moisture on oxygen concentration and carbon dioxide emitted from the FBC is shown in Figure 4.13. The percentage of carbon dioxide increases with increasing moisture content and the percentage of oxygen decreases with increasing moisture content in the rice husk particles. Fuel with different moisture contents is checked and model predictions are within satisfying limits. The actual plant data noted at different moisture percentage of rice husk particles are shown in Figure 4.13. The variation of actual plant data is in accordance with the model values. It was described by Ganesh et al. (6) that in order to achieve complete conversion of carbon it is desirable to maintain a low temperature during pyrolysis and/or partial combustion of rice husk, followed by steam gasification. The increase in moisture content in fuel causes the plant bed temperature to decrease. Bed temperature decreases because more heat is needed to convert moisture from fuel into the vapor form since a phase change takes place. Therefore, the latent heat required to change the phase is greater which causes bed temperature to decrease. Due to the lower bed temperature, complete carbon conversion occurs and causes to increased carbon dioxide concentration as shown in Figure 4.13

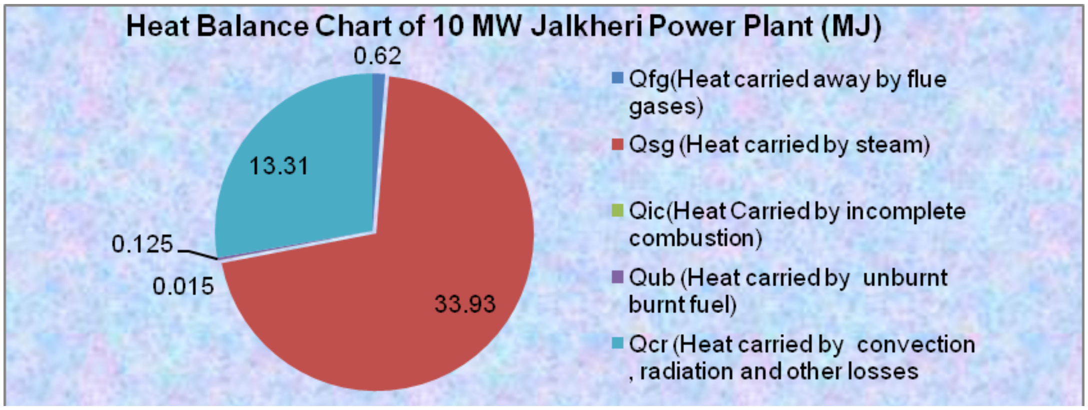


Figure 4.14 Heat Balance Chart

The heat balance boiler sheet is described in Table 4.3 and Figure 4.14. This was calculated with data collected from the plant as shown in Table 4.2 and from steam tables. The calculations were performed assuming the calorific value of rice waste is 15 MJ/kg. The total heat input to the fluidized bed boiler is 48 MJ for a mass rate of fuel entering in the combustor of 3200 g/s. From the total heat entering, 33.93 MJ of heat has been used in raising the steam. Remaining heat is gone in the losses mentioned in figure 4.14 and table 4.3. Major portion of heat loss around 13.31 MJ is gone in radiation, convection and other losses. The other losses are like leakage of steam etc. The actual boiler efficiency calculated at plant is found to be 70.68 % which is quite lower than the designed value. It is because of various losses present which need to be controlled. It is also found that some refractory plates which are used to prevent radiation losses are in damaged condition. Mass of equivalent evaporation of steam is found to be 4.697 kg/kg of fuel burnt. The average heat transfer coefficient is found to be 1101.7 W/m^2.K in bed region.

5.0 CONCLUSIONS

The above study conducted with respect to incineration of rice waste in an FBC leads to the following conclusions.

1. The CO2 percentage in the flue gas increased from 11 to 15.62 and the oxygen percentage from 10.9 to 6.4 with increases in fuel density from 0.09 to 0.12 g/cm^2, respectively.

2. U_{mf} increased from 21.64 to 28.05 cm/s, bubble diameter decreased from 20.2 to 19.65 cm/s, expanded bed height decreased from 84.7 to 82.9 cm with increases in fuel density from 0.09 to 0.12 g/cm^2, respectively.
3. U_{mf} increased from 9.44 to 43.6 cm/s, bubble diameter decreased from 21.6 to 18.8 cm, shrinkage rate decreased from 0.0462 to 0.0325 cm/s and carbon utilization efficiency increased from 96.8 to 98.75 with increases in particle size from 0.25 to 0.6 cm.
4. The shrinkage rate increased from 0.0256 to 0.0383 cm/s, bubble diameter from 19 to 20.83 cm and expanded bed height increased from 80.93 to 86.8 cm with increases in bed temperature from 925 to 1100 K. The maximum value of carbon dioxide in the flue gas was 12.55 percent and the minimum value of oxygen in the flue gas was 8.3 percent.
5. Increasing the moisture percentage in the fuel from 6.5 to 12.5 decreased the oxygen percentage from 7.3 to 6.2 in the flue gas and there was an increase in the percentage of carbon dioxide from 13.4 to 14.8 in the flue gas.
6. The actual boiler efficiency was 70.68% which is quite low, The majority of the heat losses were from radiation and convection. The average heat transfer coefficient was found to 1101.7 W/m^2.K in the bed region.

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NOTATION

U_b = Velocity of gas through bubble phase, cm/s
U_{cw} = Velocity of gas through cloud wake phase, cm/s
U_{cwn-1} = Velocity of gas through (n-1)th stage of cloud wake phase, cm/s
U_{cwn} = Velocity of gas through nth stage of cloud wake phase, cm/s
U_g = Gas velocity, cm/s
$(K_{ce})_b$ = Gas interchange co-efficient from cloud wake to emulsion phase, s^{-1}
$(K_{bc})_b$ = Gas interchange co-efficient from bubble to cloud wake phase, s^{-1},
Z = Bed height ,cm,
U_{mf} = Minimum fluidization velocity/emulsion phase gas velocity, cm/s,
U_o = Superficial gas velocity, cm/s ,
U_{cwn} = Velocity of gas through nth stage of cloud wake phase, cm/s,
C_{bn} = nth stage oxygen concentration in the bubble phase, g-mol /cm^3 ,
C_{cwn} = nth stage oxygen concentration in the cloud wake phase, g-mol /cm^3 ,
f_{cw} = Fraction of cloud wake phase in the bed,
ε_b = Volume fraction of bubbles in the bed. For detailed notations refer (1) and (3).

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