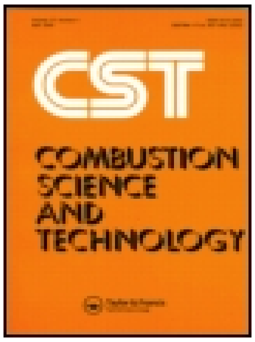

Taylor & Francis
Taylor & Francis Group

Combustion Science and Technology

ISSN: 0010-2202 (Print) 1563-521X (Online) Journal homepage: www.tandfonline.com/journals/gcst20

EFFECT OF DISTRIBUTOR DESIGN ON TEMPERATURE PROFILES IN FLUIDIZED BED DURING THE COMBUSTION OF RICE HUSK

K. V. N. SRINIVASA RAO & G. VENKAT REDDY

Combust. Sci. and Tech., 179: 1589–1603, 2007

ISSN: 0010-2202 print/1563-521X online
DOI: 10.1080/00102200701244702

Taylor & Francis
Taylor & Francis Group

Effect of Distributor Design on Temperature Profiles in Fluidized Bed During the Combustion of Rice Husk

K. V. N. Srinivasa Rao*
Department of Mechanical Engineering, Vignan's Engineering College, Vadlamudi, A.P. State, India

G. Venkat Reddy
Department Chemical Engineering, National Institute of Technology, Warangal, A.P. State, India

Abstract: The conventional method of paddy husk combustion in grate type furnaces is slow and inefficient yielding low combustion efficiency. Fluidized bed combustion of paddy husks was proved to be a feasible solution for efficient combustion along with high combustion intensity. In the present work combustion studies of rice husk were conducted in an atmospheric fluidized bed in high excess air environment with variation in distributor design. Significant changes in temperature profiles in the fluidization vessel have been observed with variation of opening area of distributor. It is found that a straight, multi-orifice type with opening area of 2.6% is appropriate distributor to maintain uniform temperatures along the bed.

Keywords: Bio-mass fuel; Burning at free board; Distributor Design; Fluidized bed; Temperature profile; Waste Utilization

Received 31 March 2006; accepted 26 January 2007.

The authors would like to acknowledge the financial support provided by the Department of Science & Technology, New Delhi, India under Young Scientist Scheme (letter no. HR/OY/E-10/98).

*Address correspondence to kvnsrao@yahoo.com

INTRODUCTION

In India about 17 million tonnes of rice husk and about 5 million tonnes of rice bran are produced annually along with about 52 million tonnes of clean rice. Agricultural wastes, like paddy and wheat straw, have significant long-term potential due to their abundant availability. It has been estimated that power requirement to the extent of 1200 MWe can be met within India by utilizing paddy and wheat straw produced in the state of Punjab alone.

Fluidized bed technology offers several unique characteristics for using biomass in small-scale energy conversion operations. Present study was undertaken to evaluate fluidized bed energy conversion method using agricultural biomass – direct combustion. A fluidized bed consists of a chamber in which solid particles are in a state of suspension by high velocity air forced upward through the particles. The turbulent mass of solid particles store heat and in turn transfers rapidly this heat to any fuel introduced into the bed.

Peel and Santos (1980) have investigated the combustion of sawdust, bagasse, rice husks, wood chips and corn cobs in a 20 cm diameter fluidized bed combustion test rig and suggested that satisfactory combustion of the bagasse, sawdust and the rice husks could be achieved with under-bed feeding only. Nienow et al. (1987) have investigated the effect of distributor design on segregation and concluded that perforated plate and standpipe distributors facilitate better mixing than a porous plate for the same superficial gas velocity. During combustion of rice husks Preto et al. (1987) have observed a considerable degree of freeboard burning of volatiles, particularly during over-bed feeding. Lin et al. (1997) conducted their experiments with a perforated steel plate distributor and straw as fuel. It has been found that when the bed is in normal fluidization state, the bed temperature is almost uniform and whenever extensive combustion of volatiles takes place in the free board results in high temperature in the free board zone rather than in the bed and a considerable amount of that heat is carried away by the outgoing gas. Combustion of rice husk carried out by Armesto et al. (2002) in a fluidized bed and temperatures have been measured along the vertical axis of combustion chamber at different heights above the distributor plate. A study of the temperature profiles shows that combustion takes place mainly between 40 and 60 cm from the distribution plate because of the combustion of volatile matter present in the rice husk. Permchart and Kouprianov (2004) have used a conical fluidized bed combustor and biomass fuels such as sawdust, rice husk and sugar cane bagasse in the experimental tests. The axial temperature profiles in the conical FBC were fairly uniform for all the fuels. From their experiments it has been found that at all excess air quantities, the rate of oxygen consumption along the combustor height was almost independent of either the nature of the biomass fuel or the combustor load. Srinivasa Rao and Venkat Reddy (2005) conducted combustion studies of rice husk in an atmospheric fluidized bed in high excess air environment (air fuel ratios 8.3–12.6) and found that when the flow rate of air was increased to 22.4 L/s (94.39% excess air) the maximum temperature of 800°C was attained in the bed because more air is available for the combustible matter. The temperatures near the distributor plate were limited to a temperature of 200°C to 300°C and an attempt is made to find temperature gradient along the bed height.

From the literature, it could be concluded that the high volatile matter contents of agricultural residues have a significant effect on the combustion mechanisms and consequently on the design and operation of the combustion systems. Due to sudden devolatilization of biomass fuels, the combustion operations should be conducted in highly excess-air environment. Not much literature is available on variation of temperature profiles due to the change in distributor plate design during the combustion of low density biomass fuels like rice husk in fluidized bed.

EXPERIMENTAL SETUP

The main chamber of circular cross-section fluidized bed combustor is fabricated with a 0.3 cm thick stainless steel material with an inner diameter of 15 cm and height 100 cm. A pressure reduction vessel of height 50 cm and diameter 35 cm is attached to the main chamber and which in turn is connected to the cyclone separator. The inner side of the vessel is coated with a castable refractory material to minimize the heat losses within the vessel. A copper tube of diameter 1.2 cm is wound around the vessel to control the bed temperature by circulating cool water through the coil. Outer side of the vessel is covered with rock wool to serve as an insulation material to reduce the heat loss from the vessel. Thermocouples and pressure taps are provided at various points to measure temperatures and pressures respectively. A provision is made to supply secondary air to meet excess air requirement. A blower is used to supply the primary and secondary air, which is connected to 10 HP DC motor. A screw feeder is used to introduce the required fuel feed into the combustion chamber. After the combustion, flue gases and solid ash particles are separated in the cyclone separator. The schematic diagram of fluidized bed combustor is presented in Figure 1.

EXPERIMENTATION

Experimental Procedure for Hydrodynamic Studies

To determine the suitable size of sand particle for good mixing with the fuel particle, three sand sizes are chosen i.e., 0.93, 0.66, and 0.4 mm.

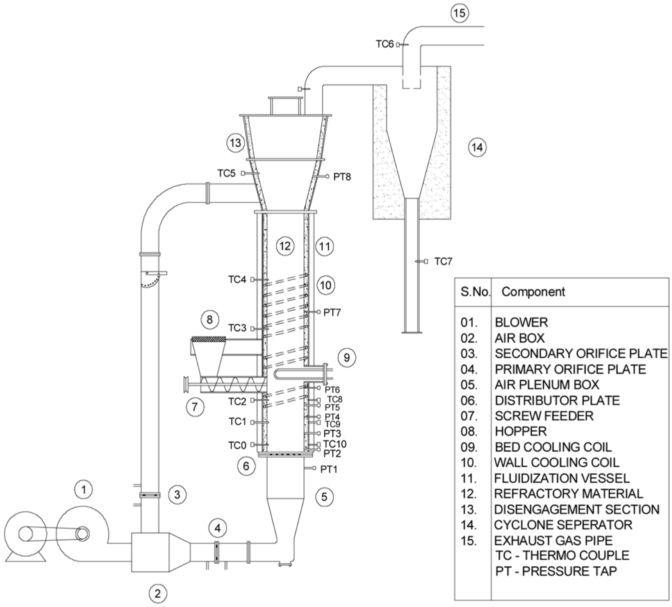

Figure 1. Experimental setup for combustion studies.

The characteristics of bed material are presented in the Table 1. Initially the sand with selected mean particle size is poured through the top of the vessel until it reaches the static bed height of 3 cm. Fuel particles are introduced above the sand bed at a height of 6 cm. The properties of fuel material and the results of proximate and ultimate analysis are presented in the Tables 2, 3 and 4 respectively. The theoretical air required for the combustion of rice husk determined from the ultimate analysis is 11.76 litre/s. A distributor plate of straight, multi-orifice type with opening area of 2.6% was designed in such a way that the primary air passing through the bed at minimum fluidization state is nearly equal to the theoretical air required for the combustion of fuel. This plate is designated as distributor

Table 1. Characteristics of bed material used for experimentation

Parameter	Sand 1	Sand 2	Sand 3
Mean particle size, d_p in mm	0.93	0.66	0.4
Particle Density, ρ_p in Kg/m^3	2520	2520	2519
Bulk Density, ρ_b in Kg/m^3	1500	1520	1600
Terminal Velocity of the particle, U_t in m/s	7.341	4.894	3.18
Static voidage, ε_o	0.4	0.392	0.36

Table 2. Properties of fuels

Property	Rice husk
Mean particle size, mm	2.1
Bulk density, kg/m^3	117.6
Particle density, kg/m^3	589.5
Calorific value, kcal/kg	3459

plate 1 and each orifice of the plate with a diameter of 1.5 mm is in a square pitch of 0.5 cm^2. The second plate with opening area of 7.6% is designated as distributor plate 2, which consists of 1100 holes in a square pitch of 0.5 cm^2 and diameter of each hole is 1.5 mm. At a bed height of 10 cm, the quantity of air required for minimum fluidization state is 15.2 litre/s with distributor plate 2. With rice husk as a fuel, the excess air corresponding to 15.2 litre/s is 29.2%. The operating conditions maintained in the bed with distributor plate 1 and distributor plate 2 are presented in Table 5.

Fluidized air is supplied through the distributor with the help of a centrifugal type blower. The amount of air supplied is measured with an orifice meter. Pressure drop across the bed is measured with the help of water filled manometer. With increase in flow rate of air through the bed, the pressure drop across the bed slowly increases. After a particular flow rate of air the pressure drop remains constant and bed get expanded along the axial height of the vessel. These bed heights are measured from the distributor plate with a scale. Due to low density of fuel particles the bed expansion is observed to be greater with fuel particles than with sand particles. The superficial velocity of airflow is given by

$$U = \frac{Volume\ flow\ rate\ of\ air}{Cross\ section\ area\ of\ vessel} m/s$$

A curve is drawn between the volume flow rate of air as abscissa and pressure drop across the bed as ordinate. The superficial velocity corresponding to the point at which pressure drop becomes constant is taken

Table 3. Proximate analysis of fuels

Property (%)	Rice husk
Moisture	9.59
Volatile matter	66.04
Ash	15.19
Fixed Carbon	9.18

Table 4. Ultimate analysis of fuels

Property (%)	Rice husk
Carbon	38.84
Hydrogen	4.82
Oxygen	33.42
Nitrogen	0.00
Sulphur	0.03

as minimum fluidization velocity. The procedure is repeated for about twelve times to achieve best possible minimum fluidization point.

Experimental Procedure for Combustion Studies

Before the fuel is burnt in the fluidized bed it is necessary to preheat the inert bed of solids to about 500°C using an auxiliary heating system. For this purpose, an over-bed LPG burner is used and a small amount of oxygen is directed at the surface of the bed. The fuel is fed through the screw feeder at a desired rate varying between 3.2 to 10.4 kg/hr. The combustion intensities ranging from 208 to 675 $kg/m^2 \cdot hr$ were attained. Thereafter the fuel feed rate is slowly increased till ash accumulation takes place over the bed. For rice husk the maximum fuel feed rate at which ash accumulation takes place was observed to be 9.8 kg/hr. At each fuel feed rate temperatures are recorded throughout the vessel with the help of

Table 5. Operating conditions of fluidized bed

S.No	Parameter	Distributor plate 1	Distributor plate 2
1	Primary air flow rate, L/s	3.12–18.47	6.88–27.7
2	Superficial velocities in the vessel, U in m/s	0.18–1.05	0.39–1.57
3	Superficial velocities in Disengagement section, m/s	0.04–0.26	0.1–0.39
4	Voidage at minimum fluidization state, ε_{mf}	0.49	0.49
5	Pressure drop at minimum fluidization, $(\Delta p)_{mf}$ in N/m^2	1532.63	1390.3
6	Static bed height of sand, L_s in cm	10	10
7	Minimum fluidization velocity, U_{mf} in m/s	0.66	0.86
8	Bed height at minimum fluidization, L_{mf} in cm	12.4	11.6

thermocouples. In the next phase of experimentation at each primary air flow rate, secondary air is also supplied at the disengagement section. The temperature changes in the vessel are measured and then gradually the percentage of secondary air is increased and all the parameters are noted.

Uncertainty Analysis

The uncertainties associated with the experimental data are estimated in this section. Let us assume that z is a given function of the independent variables ($x_1, x_2, x_3, x_4, \ldots\ldots\ldots, x_n$). Let ω_z be the uncertainty in z and $\omega_1, \omega_2, \omega_3, \omega_4, \ldots\ldots\ldots\ldots, \omega_n$, be the uncertainty in the dependent variables. If the uncertainties in the independent variables are given in the same odds, then the uncertainty in z having these odd is given by Holman (1984) as,

$$\omega_h = \left[\left(\frac{\partial z}{\partial x_1}\omega_1\right)^2 + \left(\frac{\partial z}{\partial x_2}\omega_2\right)^2 + \cdots\cdots\cdots\cdots + \left(\frac{\partial z}{\partial x_n}\omega_n\right)^2\right]^{\frac{1}{2}} \quad (1)$$

$$\frac{\omega_h}{h} = \left[\left(\frac{\omega_1}{x_1}\right)^2 + \left(\frac{\omega_2}{x_2}\right)^2 + \cdots\cdots\cdots\cdots + \left(\frac{\omega_n}{x_n}\right)^2\right]^{\frac{1}{2}} \quad (2)$$

From the above relations its is found that the uncertainties in superficial velocity are in the range of 8.09 to 11.116% and the uncertainties encountered in experimental investigations of fuel feed rate is estimated around 0.12% to 0.18%. The uncertainty during the calculation of combustion efficiency for different fuels and at different operating conditions is in the range of 0.341% to 0.6578%.

RESULTS AND ANALYSIS

Effect of Distributor Design on Minimum Fluidization Velocity

It was found from the cold bed studies that the sand particle of size 0.4 mm is appropriate for better hydrodynamic behaviour of the bed for the fuels selected in the present study. The plots of pressure drop, Δp against the superficial velocity, U are shown in Figures 2 and 3. The minimum fluidization velocity was found to be 0.6 m/s for the distributor plate 1 and 0.86 m/s for the distributor plate 2. The reason for the low value of minimum fluidization velocity in the distributor plate 1 against distributor plate 2 may be due to higher velocity of air through each orifice of the distributor plate. As the flow rate of air was increased,

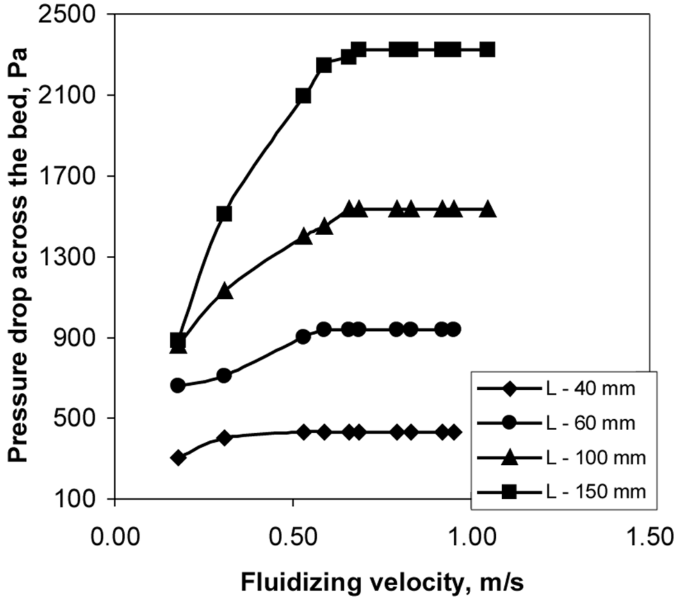

Figure 2. Pressure drop across the bed aganist fluidizing velocity at different static bed heights with distributor plate 1.

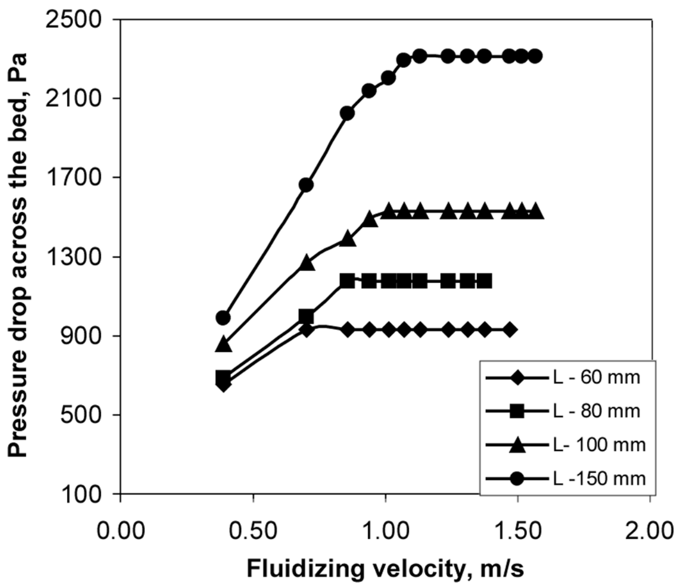

Figure 3. Pressure drop across the bed against fluidizing velocity at different static bed heights with distributor plate 2.

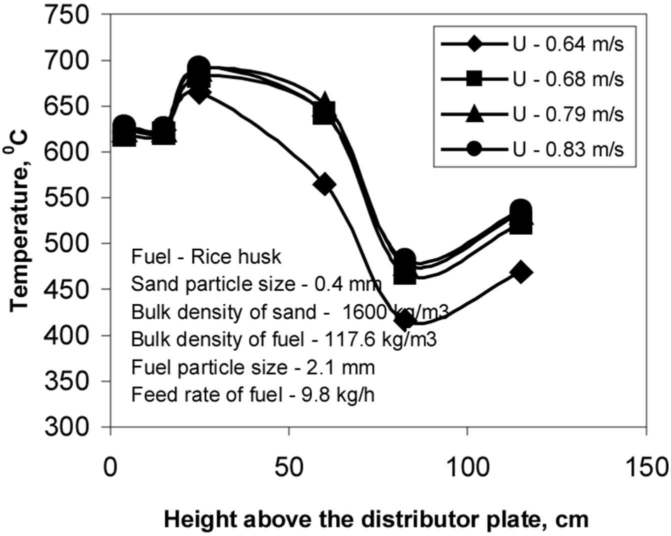

Figure 4. Effect of fluidizing velocity on temperature profile at different heights above the distributor plate 1.

the pressure drop across the distributor plate increased because of less number of orifices in distributor plate 1 and consequently the velocity of air through each orifice increased.

Effect of Fluidizing Velocity on Temperature Profile in the Combustion Chamber

With distributor plate 1 the experiments with rice husk were conducted for about 3 hours duration in a steady state at a constant feed rate of 9.8 kg/h with the primary air flow rate varying between 11.62 to 14.64 litre/s. The temperature profiles along the vessel above the distributor plate at different fluidizing velocities is shown in Figure 4. At minimum fluidization state the temperatures near the distributor zone were found to be around 630°C. The temperature is observed to increase gradually to 665°C at a bed height of 25 cm and thereafter the temperature decreased with the increase in height above the distributor plate and again a small rise of 50°C is observed at a height of 115 cm. This temperature rise is due to enlarged free board. In the enlarged free board because of increased diameter from 15 cm to 40 cm, there is sudden drop in the fluidization velocity and therefore residence time increases which facilitates further combustion; as a result the temperature in the free board increases. As the fluidizing velocity was increased the temperatures at

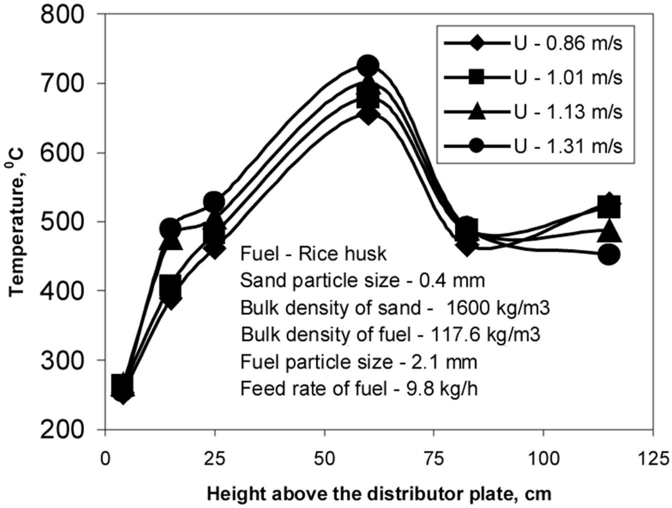

Figure 5. Effect of fluidizing velocity on temperature profiles along axial height above the distributor plate 2.

all the sections along the height was also found to increase, except near the distributor zone where appreciable change in temperature was not observed. It may be due to improper mixing of fuel with the bed material at low bed heights.

Similar tests were conducted with rice husk as fuel material at the same feed rate of 9.8 kg/h by replacing distributor plate 1 with 2. As shown in Figure 5, it is observed that in the active fluidized bed (i.e., up to 25 cm), the temperature gradient is more with distributor plate 2 when compared with distributor plate 1, which is undesirable. The peak temperature point is shifted abnormally to a height of 60 cm and it indicates combustion of fuel particles is not tacking place in the bed of solid particles. Therefore, a high amount of heat released during the combustion is lost through the flue gases without much retention of heat within the solid bed.

Near the distributor zone very low temperatures (260°C) were noticed. There is a gradual temperature rise up to 60 cm height from the bed and thereafter a drop in temperature is observed. Again in the enlarged free board a small rise in temperature is noticed. The significant change is the maximum temperature occurred at a height of 60 cm as against 25 cm noticed with distributor plate 1. The reason may be attributed to the fact that because of relatively higher minimum fluidization velocity, the fuel particles having low bulk density (117.6 kg/m^3) are floating to certain height before the complete combustion is taking place within the bed and this inturn leads to temperature gradient along the bed height and non-uniform heat release during the combustion. Similar tendencies have also been observed by Preto et al. (1987) during the combustion of rice husk and wood chips. During over-bed feeding, there is an increased freeboard combustion, which leads to an increased freeboard temperature. Rajaram and Mallaiah (1987) have observed that the free board temperatures are more by 100°C than the bed temperature for rice husk as against 200 to 250°C noticed in the present case with distributor plate 2. When combustion studies were performed with the distributor plate 1, the difference in temperature between the bed and free board is reduced to 60–80°C.

The active combustion of fuel particles takes place between 15 and 60 cm height above the distributor plate. Armesto et al. (2002) carried out combustion of rice husk in a fluidized bed combustor and obtained a maximum temperature corresponding to the zone at 40 cm from the distribution plate. Above this height the temperature decreased slowly or remained constant until the end of the expanded bed and beyond that the temperature decreased rapidly. It is also reported that these temperature profiles indicate that the combustion process is produced mainly between 40 and 60 cm above the distribution plate against 15 to 60 cm in the present study.

Effect of Feed Rate on Temperature Profile in the Combustion Chamber

The fuel is fed through a variable speed screw feeder at a desired rate and fuel feed rate is varied from 3.2 to 10.4 kg/hr. The combustion intensity is defined as the fuel feed rate into the fluidization vessel per unit area available for burning. The combustion intensities ranging from 208 to 675 kg/ m^2-hr are attained. The fuel feed rate is gradually increased till ash accumulation takes place over the bed. As the ash is accumulated over the bed, it leads to defluidization of the bed. This condition is indicated by a sudden reduction in the pressure across the bed. For rice husk the maximum fuel feed rate is observed to be 9.8 kg/hr. At very low feed rates, the combustion is intermittent due to high air-fuel ratio as the velocity air passing through the bed is maintained at constant flow rate. It is found that, to sustain the combustion process, feed rate at the minimum fluidization velocity for rice husk is 6.6 kg/h.

Now at the same minimum fluidization velocity, feed rate of fuel is increased till the maximum possible temperatures are attained in the combustion chamber. These temperature profiles are depicted in Figures 6 and 7 for distributor plate 1 and distributor plate 2 respectively. In both the cases at lower feed rates the temperatures at different heights are more uniform and as the feed rate increases, a considerable raise in the temperatures are observed at all the points along the bed height.

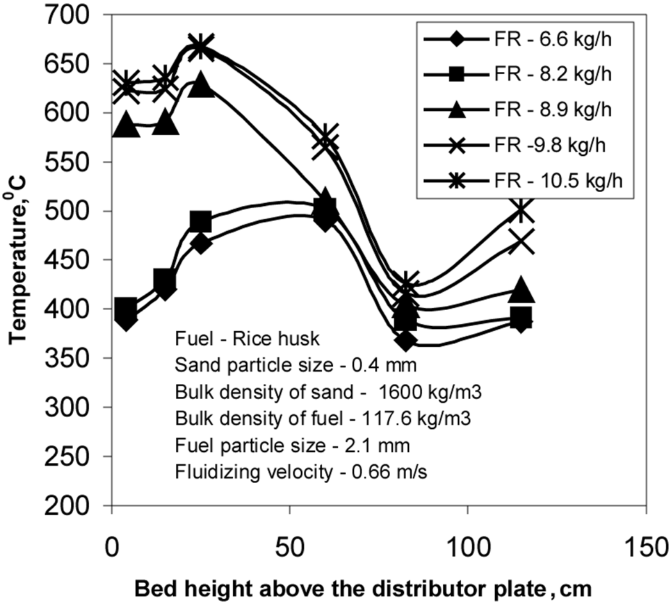

Figure 6. Effect of feed rate on temperature profile along the axial height above the distributor plate 1.

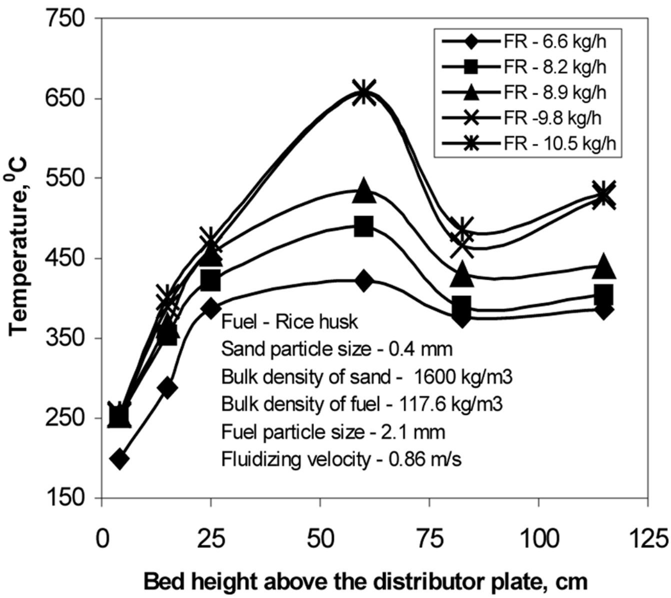

Figure 7. Effect of feed rate on temperature profiles along axial height above the distributor plate 2.

As shown in Figure 6, with the increase in feed rate beyond 8.9 kg/h a sudden temperature rise is observed along the axial height above the distributor plate.

It is also noticed that nearly uniform temperatures are prevailed within the bed and temperature drop is observed in the free board. On the other hand, with distributor plate 2, as the feed rate is increased beyond 8.9 kg/h, the temperature increase is steep in the free board when compared to different heights above the distributor plate as shown in Figure 7.

This indicates that the large amount of heat released during combustion is carried through the flue gas. Another notable feature is at low feed rates there is no temperature rise in the enlarged free board which indicates that no combustion is taking place in this section and the burning of particles is completed before it reaches enlarged section.

Effect of Secondary Air on Temperature Profile in the Combustion Chamber

To achieve higher combustion efficiency, the primary air is passed through the distributor plate at a rate slightly more than that required

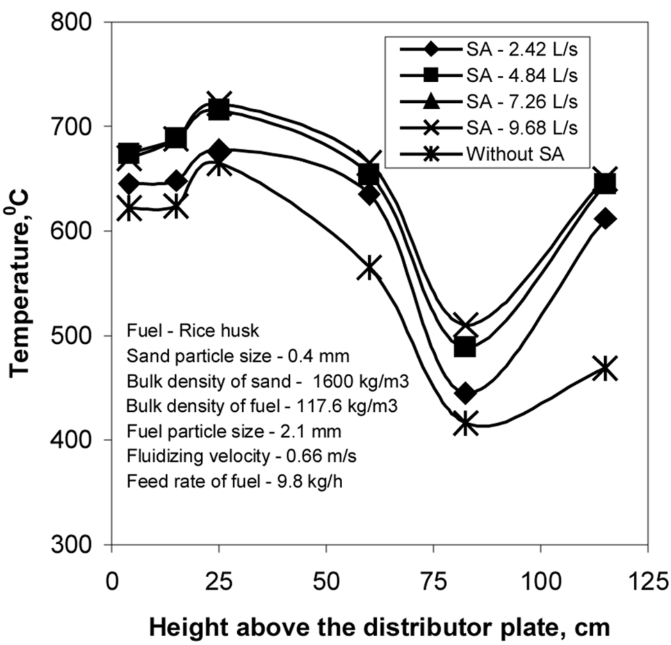

Figure 8. Effect of secondary air on temperature profile along the axial height above the distributor plate 1.

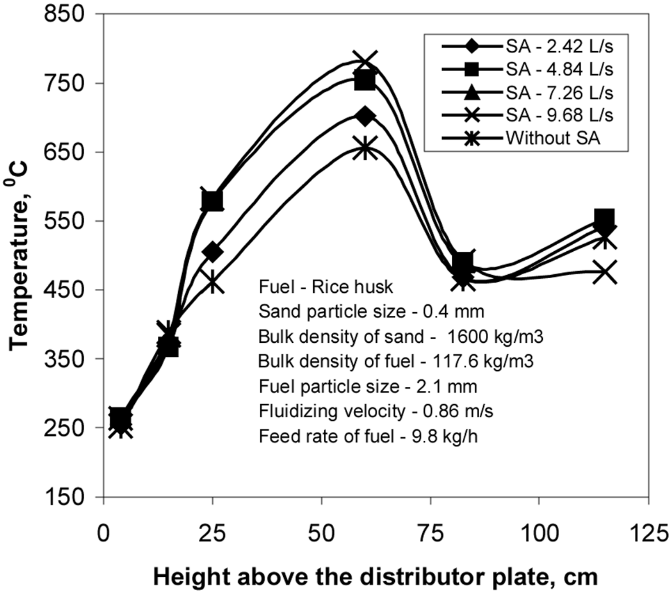

Figure 9. Effect of secondary air on temperature profiles along axial height above the distributor plate 2.

for char combustion and the remaining excess air is supplied as secondary air before the enlarged section of freeboard. A substantial increase in the temperatures throughout the combustor is observed as shown in Figures 8 and 9. A considerable rise in temperature at the enlarged free board is also observed. This indicates that air staging can improve combustion. While using rice husk as a fuel, at fluidizing velocity of 1.13 m/s (primary airflow rate of 20 litre/s, 70% excess air), the maximum temperature at a height of 60 cm is observed to be 701°C (Figure 5). Almost the same peak temperature is obtained with 15.2 litre/s primary air and 4.84 litre/s secondary air (67.47% excess air) as shown in Figure 9. Also the temperature at the enlarged free board was observed to be 541°C against 487°C observed at primary airflow rate of 20 litre/s. It indicates that considerable burning of carbon particles has taken place at this section because of high turbulence created with secondary air.

CONCLUSIONS

1. The axial temperature profiles in the fluidized bed combustion chamber are not uniform for rice husk at all operating conditions. It is observed that the effect of distributor plate on temperature profile

within the bed is prominent. The significant change that has been observed with rice husk is the maximum temperature at a height of 60 cm with distributor plate 2 as against 25 cm noticed with distributor plate 1.

2. The maximum temperature at all the velocities is obtained at a height of 25 cm from the distributor plate and then a gradual drop in temperatures up to a height of 82.5 cm. Again rise in the temperature at a height of 115 cm above the distributor plate 1 is noticed; and that indicates a considerable burning of fuel is taking place in the freeboard.
3. A rise in temperature at the height of 115 cm above the distributor plate is found due to enlarged disengagement section.
4. With supply of secondary air before the enlarged section of freeboard a substantial increase in the temperature through out the combustor has been observed for rice husk.

REFERENCES

Armesto, L., Bahillo, A., Veijonen, K., Cabanillas, A., and Otero, J. (2002) Combustion behaviour of rice husk in a bubbling fluidized bed. *Biomass Bioener.*, **23**, 171–179.

Lin, L., Gitte, K., Kim, D.J., Esther, M., and Bank, L. (1997) Agglomeration phenomena in fluidized bed combustion of straw. In *Proc. of the 14th International Conference on Fluidized Bed Combustion*, ASME, Vancouver, New York, Canada, pp. 831–837.

Nienow, A.W., Naimer, N.S., and Chiba, J. (1987) Studies of segregation/mixing in fluidized beds of different size particles. *Chem. Eng. Comm.*, **62**, 53–66.

Peel, R.B. and Santos, F.J. (1980) Fluidized bed combustion of vegetable fuels. In *Proc. Fluidized Combustion-Systems and Applications*, Institute of Energy Symposium Series 4, London, UK, p. IIB2.

Permchart, W. and Kouprianov, V.I. (2004) Emission performance and combustion efficiency of a conical fluidized-bed combustor firing various biomass fuels. *Bioresource Technology*, V **92**, 83–91.

Preto, F., Anthony, E.J., Desai, D.L., and Friedrich, F.D. (1987) Combustion trails of rice hulls in a pilot-scale fluidized bed. In *Proc. of 9th International Conference on Fluidized bed Combustion*, American Society of Mechanical Engineers (ASME), Boston May 3–7, pp. 1123–1127.

Rajaram, S. and Mallaiah, K.T.U. (1987) A 10 MW_e fluidized bed power plant for paddy straw. In *Proc. of 9th International Conference on Fluidized Bed Combustion*, American Society of Mechanical Engineers (ASME), Boston May 3–7, 392–397.

Srinivasa Rao, K.V.N. and Venkat Reddy, G. (2005) Combustion studies of rice husk in fluidized bed. *J. Water Ener. Inter.*, **62**(2), 22–28.