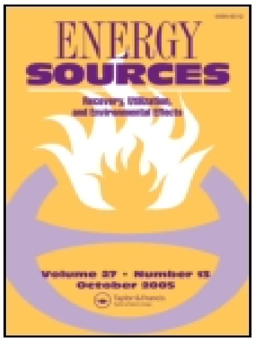

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Energy Sources, Part A: Recovery, Utilization, and Environmental Effects

ISSN: 1556-7036 (Print) 1556-7230 (Online) Journal homepage: www.tandfonline.com/journals/ueso20

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Energy Sources, Part A, 33:2181–2193, 2011

ISSN: 1556-7036 print/1556-7230 online
DOI: 10.1080/15567030903515112

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Comparison of the Combustion Characteristics of Rice Husk, Sawdust, and Groundnut Shells in a Bubbling Fluidized Bed

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Abstract *Agricultural residues, such as rice husk, sawdust, wood waste, groundnut shells, etc., could play an important role as energy sources. These biomass fuels are difficult to handle due to high moisture and fines content and also due to fuel ash softening at relatively low temperatures. Fluidized bed energy technology offers several unique characteristics for using biomass in small-scale energy conversion operations. In the present work, combustion studies of rice husk, sawdust, and groundnut shells were conducted in an atmospheric bubbling fluidized bed in high excess air environment and observed considerable reduction in CO levels in flue gases and unburned carbon in residual ash. The combustion efficiency, temperature distribution in the reactor, ash characteristics, etc. are also studied in a fluidized bed at various operating conditions. Secondary air is introduced in the enlarged free board to provide high turbulence for flue gases and unburned particles in the reactor vessel.*

Keywords biomass fuels, fluidized bed, free board burning, high combustion efficiency, low CO emission, waste utilization

Introduction

Large quantities of agricultural residues are produced each year in the countries like India and China and, consequently, large investments are needed for collection, transportation, and storage, which make many of these residues economically unattractive. For example, in India about 17 million tons (dry mass basis) of rice husk is produced annually. It has been estimated that the power requirement to the extent of 1,200 MWe can be met within India by utilization of paddy and wheat straw produced in the state of Punjab (Jenkins and Bhatnagar, 1991) alone. Biomass fuels cannot be burned effectively in the conventional system due to their diverse physical and chemical properties. A fluidized combustion boiler can effectively overcome all the problems associated with conventional systems and it can burn biomass fuels in an efficient and environmentally acceptable manner. A fluidized bed consists of inert particles, such as sand, through which fluidizing air

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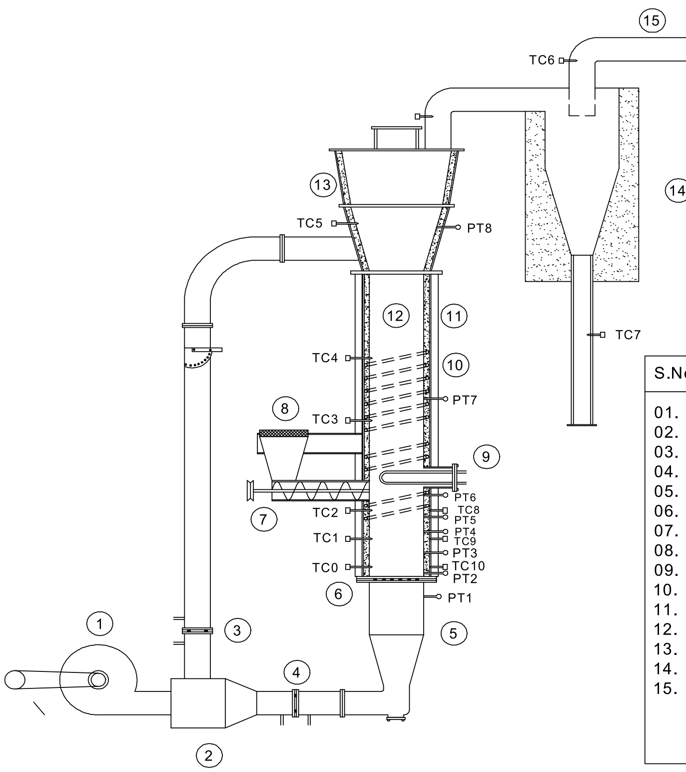
can be passed via a distributor plate at the bottom. Under normal operating conditions, the bed contains only a small percentage of burning fuel (around 1 to 2%), so that the inert particles transport the heat away from the burning particles, thereby keeping their temperature below the levels at which ash melts.

Lepori et al. (1980) have suggested that fluidized bed energy technology offers several unique characteristics for using biomass in small-scale energy conversion operations. Bhattacharya et al. (1983) have reported that a significant carryover of inert sand particles from the bed has been observed under conditions of high airflow rate. During combustion of rice husks, Preto et al. (1987) have observed a considerable degree of freeboard burning of volatiles, particularly during over-bed feeding. The fluidizing velocities have been varied from 0.4 to 2.2 m/s with excess air levels 30–95%. The bed temperatures were maintained between 650–900°C. The higher CO emissions have been observed at higher fluidization velocities and this could be because of shorter residence time. Bhattacharya and Weizhang (1990) have determined the loss of combustibles from the fluidized bed combustor. The loss due to unburned carbon in the ash has been found to be typically 1–3%, but the loss due to CO formation is higher, at about 3–10%. As the rice husk contains high volatile matter, a considerable degree of free board burning of volatiles has been observed. Salour et al. (1993) have found that the combustion efficiency is dependent on the fuel particle size, excess air level, and bed temperature and gas velocity in bubbling beds. It is recommended that the height of free board must be increased to increase the combustion efficiencies. Lin et al. (1997) fired wheat straw in a fluidized bed, and a combustion model for wheat straw has been discussed. The wheat straw has been burned in a fluidized bed and its combustion characteristics have been compared with bituminous coal by Jones (1999). Khraisha et al. (1999) studied the combustion of olive cake in a fluidized bed. Saenger et al. (2001) reported the combustion mechanism of two types of coffee husks using a pilot-scale fluidized bed facility (FBC). Armesto et al. (2002) have reported that during the combustion of rice husk in a fluidized bed the CO emissions increase with an increase in fluidizing velocity. Permchart and Kouprianov (2004) revealed that for the maximum combustor load and excess air of 50–100%, a combustion efficiency of over 99% could be achieved when firing sawdust and bagasse. The maximum combustion efficiency of 86% has been achieved with rice husk at an excess air of about 60%. 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. The temperature near the distributor plate was limited to 200 to 300°C and temperature gradient along the bed height was found. Srinivasa Rao and Venkat Reddy (2007) investigated combustion studies of rice husk in an atmospheric fluidized bed with variation in distributor design. Significant changes in temperature profiles in the fluidization vessel have been observed with variation of the opening area of the distributor. It is concluded that a straight, multi-orifice type with an opening area of 2.6% is an appropriate distributor to maintain uniform temperatures along the bed. Combustion of sawdust in a fluidized bed was studied in the presence of secondary air injection and it was found that the maximum possible combustion efficiency with sawdust was 99.2% at 65% of excess air (Srinivasa Rao and Venkat Reddy, 2008).

From the literature it is found that the control of combustion of biomass fuels is expected to be difficult and appropriate operating conditions have to be investigated for stable operation. The CO emissions in the flue gas were reported to be still in higher quantities. Therefore, in the present work an attempt has been made to determine combustion characteristics of rice husk, sawdust, and groundnut shells in a bubbling fluidized bed and the results are compared.

Experimental Setup

A circular cross-section fluidized bed combustor is fabricated with an inner diameter of 150 mm, and a main combustion chamber with a height of 1,000 mm is made with a stainless steel material of 10-mm thickness. A pressure reduction vessel is attached to the main chamber with a height of 500 mm and a diameter of 350 mm, which is connected to the cyclone separator. The inner side of the vessel is coated with a castable refractory material to minimize the heat losses in the vessel. A copper tube with a diameter of 12 mm is wound around the vessel to control the bed temperature by circulating cooling water through the coil. The outer side of the vessel is covered with rock wool as an insulation material to reduce the heat transfer from the vessel. Thermocouples and pressure taps are provided at various points to measure temperatures and pressures respectively. A secondary air provision is also provided to supply excess air requirement. A blower is used to supply the primary and secondary air, which is connected to 10 H.P. D.C. motor. A screw feeder is used to provide the required fuel feed into the combustion chamber. Afterward the combustion flue gases and solid ash particles are separated in the cyclone separator. The schematic diagram of the fluidized bed combustor is presented in Figure 1.



S.No.	Component
01.	BLOWER
02.	AIR BOX
03.	SECONDARY ORIFICE PLATE
04.	PRIMARY ORIFICE PLATE
05.	AIR PLENUM BOX
06.	DISTRIBUTOR PLATE
07.	SCREW FEEDER
08.	HOPPER
09.	BED COOLING COIL
10.	WALL COOLING COIL
11.	FLUIDIZATION VESSLE
12.	REFRACTORY MATERIAL
13.	DISENGAGEMENT SECTION
14.	CYCLONE SEPERATOR
15.	EXHAUST GAS PIPE
	TC - THERMO COUPLE
	PT - PRESSURE TAP

Figure 1. Experimental set-up for combustion studies.

Experimentation

The characteristics of bed material are presented in the Table 1. Fuel particles are introduced above the sand bed and their properties are given in Table 2. From the cold flow studies it is found that a sand particle of size 0.4 mm is most suitable for fuels to achieve low minimum fluidization point and good mixing with fuel particles without segregation characteristics. Proximate analysis of fuel is done as per the procedure of the code IS 1350 (part 1)–1984. Ultimate analysis constitutes the determination of total carbon, hydrogen, nitrogen, oxygen, and sulphur percentages in fuel. The analysis for the selected fuels is carried out as per specifications of IS: 1350 (part IV)–1974. The proximate and ultimate analyses of fuels are given in Tables 3 and 4. The airflow rate through the bed was increased until it reaches a fluidization state. Pressure taps are

Table 1
Characteristics of bed material used for experimentation

Sample no.	Parameter	Sand
1	Mean particle size, d_p in mm	0.404
2	Max. size of particle, mm	0.542
3	Min. size of particle, mm	0.27
4	Particle density, ρ_p in kg/m^3	2,519
5	Bulk density, ρ_b in kg/m^3	1,600
6	Terminal velocity of the particle, U_t in m/s	3.18
7	Static voidage, ε_o	0.36
8	Spherocity, ϕ_s	0.67

Table 2
Properties of fuels

Property	Rice husk	Saw dust	Groundnut shell
Average diameter of particle, mm	2.094	0.578	8.78
Bulk density, kg/m^3	117.6	286.4	120.3
Particle density, kg/m^3	589.5	716.2	680.4
Calorific value, MJ/kg	14.482	18.690	19.937

Table 3
Proximate analysis of fuels

Property (by mass)	Rice husk	Saw dust	Groundnut shell
Moisture, %	9.59	8.15	12.07
Volatile matter, %	66.043	81.17	82.12
Ash, %	15.089	1.994	1.8
Fixed carbon, %	9.178	8.686	4.063

Table 4
Ultimate analysis of fuels

Property (by mass)	Rice husk	Saw dust	Groundnut shell
Carbon, %	38.84	48.496	48.6
Hydrogen, %	4.82	3.96	5.35
Oxygen, %	33.42	27.15	31.5
Nitrogen, %	0.00	0.24	0.68
Sulpher, %	0.03	0.01	0.00

provided along the axial length of the vertical vessel at regular intervals and are connected to water glass manometers to measure the pressure drop across the bed and distributor. The operating conditions of fluidized bed are presented in Table 5. Before fuel particles are burned in the fluidized bed, it is necessary to heat the inert bed of solids to about 500°C using an auxiliary heating system. An over-bed LPG burner with a small amount of oxygen is directed at the surface of the bed for preheating purposes. Once the bed has reached the required temperature, then fuel particles are slowly supplied through the screw feeder into the bed. As the temperature is increasing in the bed, the initial startup system is removed from the bed and the feed rate is continued until the bed has reached the stable temperature. Normally, about 2 to 3 h are required for preheating the bed. Initial combustion tests revealed that 30 to 45 min was required to reach stable bed operating temperatures after the initiating fuel feed. The total air required for combustion of different biomass fuels has been supplied in two streams. The primary air is passed through the distributor plate and the secondary air is supplied at the disengagement section or enlarged free board. After initial startup of the bed, the flow rate of primary air is increased until the bed reaches the minimum fluidization state. The theoretical air required for the combustion of the fuel particle has been calculated from the ultimate analysis, and excess airflow rate is determined. To determine the carbon loss during the combustion process, ash is collected from the cyclone separator and proximate analysis is carried out to determine the carbon present in the residual ash. The carbon monoxide

Table 5
Operating conditions of fluidized bed

Sample no.	Parameter	Sand
1	Air flow rate, m^3/s	0.00312–0.01847
2	Superficial velocities in the vessel, U_g in m/s	0.18–1.05
3	Superficial velocities in disengagement section, m/s	0.04–0.26
4	Voidage at minimum fluidization state, ε_{mf}	0.49
5	Pressure drop at minimum fluidization, $(\Delta p)_{mf}$ in N/m^2	1,532.63
6	Static bed height of inert particles, L_s in mm	100
7	Minimum fluidization velocity, U_{mf} in m/s	0.66
8	Bed height at minimum fluidization, L_{mf} in mm	116

in the flue gas is measured using a flue gas analyzer (with a measuring gas intake of 3 to 8 l/min and response time of <10 sec), which gives the percentage of volume of CO per unit volume of flue gas released through the exhaust end. From the ultimate analysis, the carbon content of the fuel can be assessed. The distributor plate is a straight multi-orifice type with an opening area of 7.6%.

Thus, the combustion efficiency is calculated with the following equation:

Combustion efficiency = [Calorific value of rice husk

− (Heating value of refuse at cyclone separator

+ Heating value in the flue gasses)]/Calorific value of rice husk,

$$\eta_c = \frac{CV - (HVR + HVG)}{CV},$$

$$\eta_c = \frac{CV - [(W_c \times CVC) + (W_{co} \times CVCO)]}{CV},$$

where

CV = Calorific value of fuel, kJ/kg,
CVC = Calorific value of carbon, kJ/kg,
$CVCO$ = Calorific value of carbon monoxide, kJ/kg,
W_c = Weight of carbon in refuse, kg,

W_{co} = Weight of carbon monoxide in flue gases, kg.

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 $(x_1, x_2, x_3, x_4, \ldots, x_n)$. Let ω_z be the uncertainty in z and $\omega_1, \omega_2, \omega_3, \omega_4, \ldots, \omega_n$ be the uncertainty in the dependent variables. If the uncertainties in the independent variables are given at the same odds, then the uncertainty of z having these odds is given by Holman (1984) as:

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

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

From the above equations it 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 combustion efficiency for different fuels and under different operating conditions are in the range of 0.341 to 0.6578%.

Results and Discussion

The maximum feed rates of rice husk, saw dust and groundnut shells are observed at 9.8, 10.2, and 9.3 kg/h, respectively. As the feed rate is increased further, ash agglomeration is found to take place over the bed and this leads to defluidization of the bed. The comparison of temperature profiles of three different fuels is presented in Figures 2 and 3. At higher feed rates the three fuels exhibited different characteristics. With groundnut shells, high temperatures are noticed at all the locations and temperature profile of sawdust closely follows the profile of groundnut shells. For rice husk, particularly, at lower bed heights, low temperatures are observed with respect to the other fuels. The temperatures are more uniform after 600 mm height above the distributor plate (Figure 2). Due to high silica content in rice husk in comparison with the other two fuels, the combustion of rice husk within the bed is less. The active combustion of fuel particles takes place between 150 and 600 mm 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 400 mm from the distribution plate. The tendency of variation in temperature is greatly reduced at lower feed rates as shown in Figure 3. Another notable feature is that at low feed rates, no temperature rise in the enlarged free board is noticed, which indicates that no combustion is taking place in this section and the burning of particles is completed before it reaches an enlarged section.

Effect of Excess Air on Carbon Carry over Loss in Combustion Chamber

A part of the energy released during the combustion process is lost either through CO present in the flue gas or in the form of unburned combustibles along with the ash.

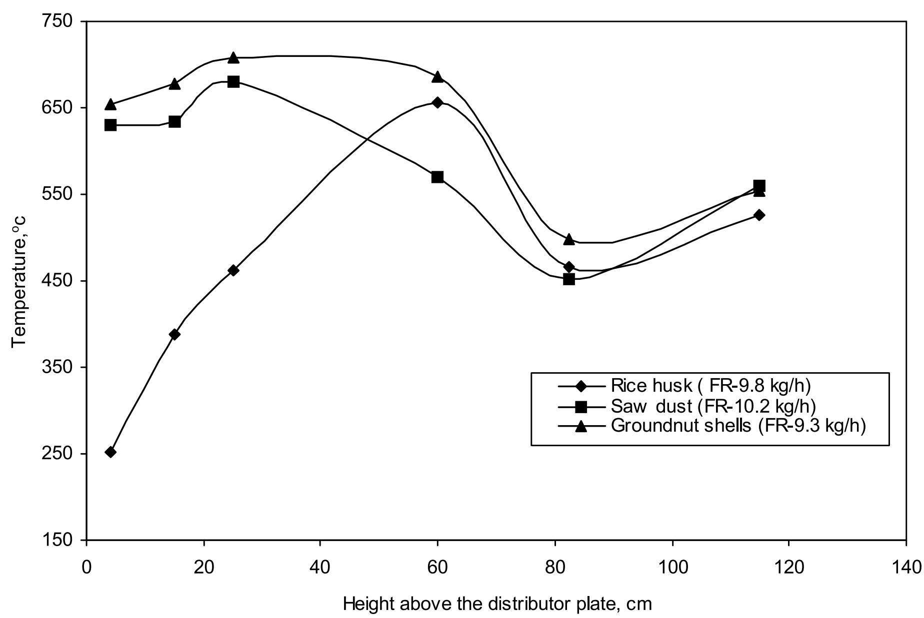


Figure 2. Comparison of temperature profiles of different biomass fuels at a constant superficial velocity of 0.86 m/s and at maximum feed rate.

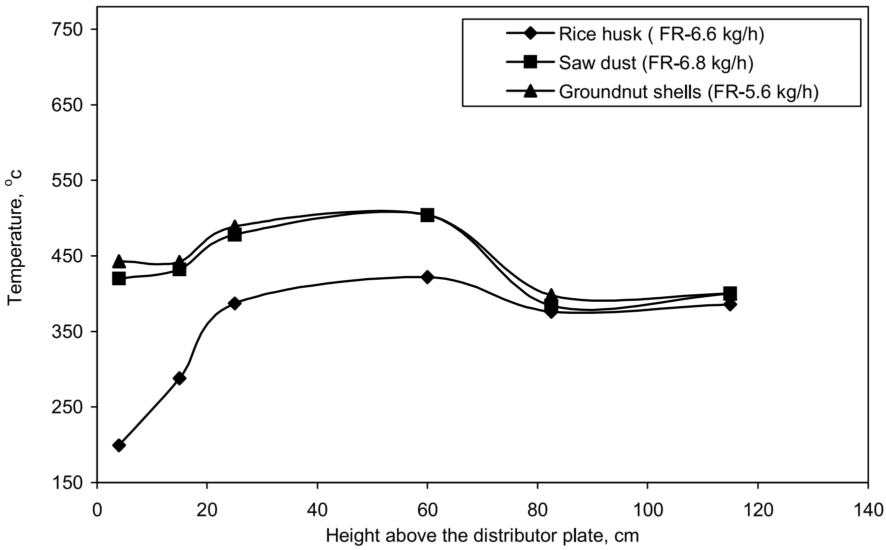


Figure 3. Comparison of temperature profiles of different biomass fuels at a constant superficial velocity of 0.86 m/s at lower feed rates.

Figure 4 represents the heat loss owing to the incomplete combustion of fuel (i.e., carbon monoxide formation during the combustion process) against the fluidizing velocity, when firing the fuels at maximum combustor loading. It has been observed that the CO formation for rice husk is greater than that for sawdust and groundnut shells at fluidizing velocities less than 0.9 m/s. With an increase in air velocity, the percentage of CO is found to decrease for all the fuels. But the reduction of the CO level is significant for rice

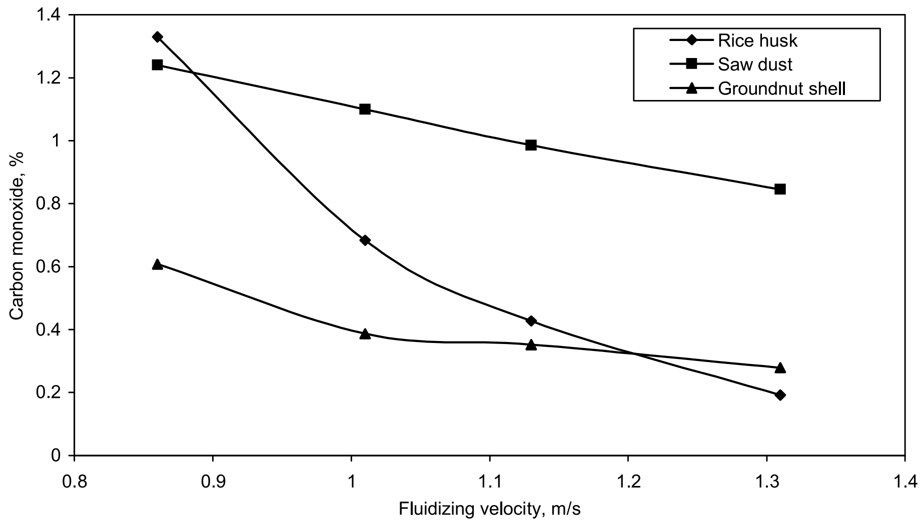


Figure 4. Effect of fluidizing velocity on carbon monoxide leaving with flue gas at cyclone separator for different biomass fuels.

husk when compared with other fuels. Much change in CO levels has not been observed beyond the fluidizing velocity of 1.1 m/s for all the fuels. The minimum CO emissions are observed to be 0.192, 0.845, and 0.279% for rice husk, sawdust, and groundnut shells, respectively. The higher CO levels for saw dust and groundnut shells is attributed to the fact that incomplete combustion of volatile matter of these fuels means that the fluidizing velocity is going to influence these emissions.

Staged combustion, i.e., splitting the air required for combustion into primary air and secondary air, is found to be an effective way of ensuring high combustion efficiency and, consequently, low emissions of the unburned pollutants. The corresponding heat loss against excess air for the same fuel loading is shown in Figure 5. For all the fuels, CO levels are seen to decrease drastically even at low excess air. With rice husk, the CO emission was 2.7% at 20% of excess air, when supplied as primary air. It is reduced to 1.89% for the same amount of excess air, when supplied as secondary air. This reduction in CO levels may be ascribed to high turbulence created by the supply of secondary air that had led to more combustion of volatile matter.

Figure 6 shows the effect of heat loss owing to carbon carry over along with ash against fluidizing velocity. When fluidizing velocity is more than 1.1 m/s, a steep rise in carbon loss for rice husk and a slight increase in the percentage of carbon loss for sawdust and groundnut shells have been observed. The carbon loss tends to increase as the fluidization velocity is increased further. The carbon loss can be reduced significantly with the supply of excess air as secondary air near the enlarged freeboard region as depicted in Figure 7. For rice husk, the carbon loss is almost constant with the value around 7% in the region between 20 to 60% of excess air and marginal increase after 60% of excess air. For sawdust and groundnut shells, the carbon loss is in the range of 0.5 to 0.4% with the increase in excess air.

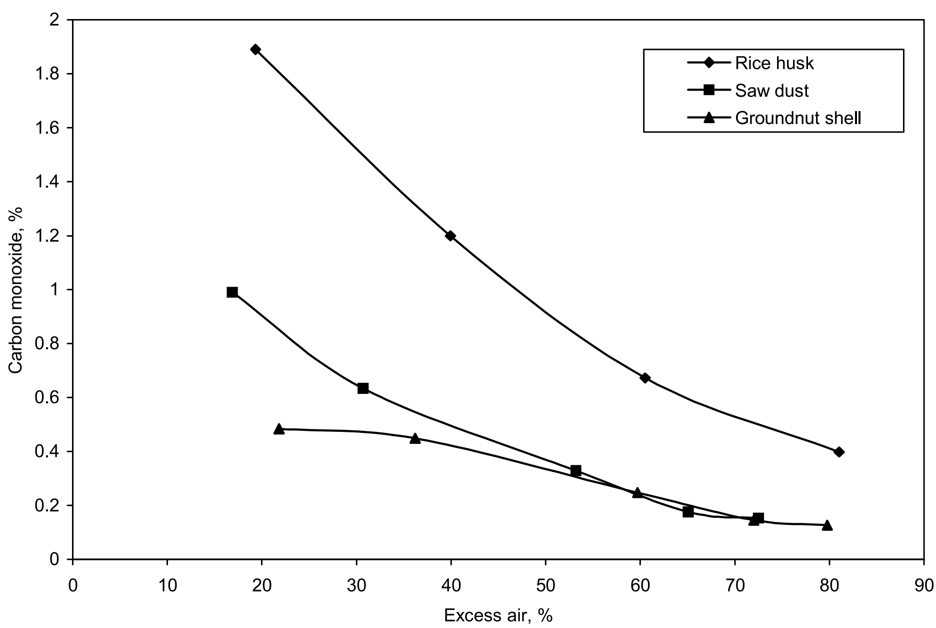


Figure 5. Effect of excess air on carbon monoxide leaving with flue gas at cyclone separator for different biomass fuels.

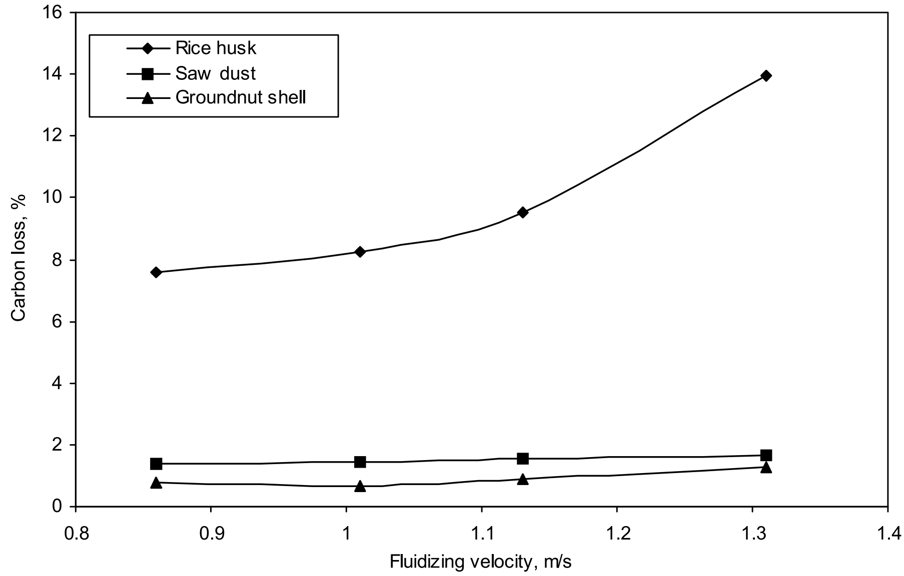


Figure 6. Effect of fluidizing velocity on carbon carry over along with ash at cyclone separator for different biomass fuels.

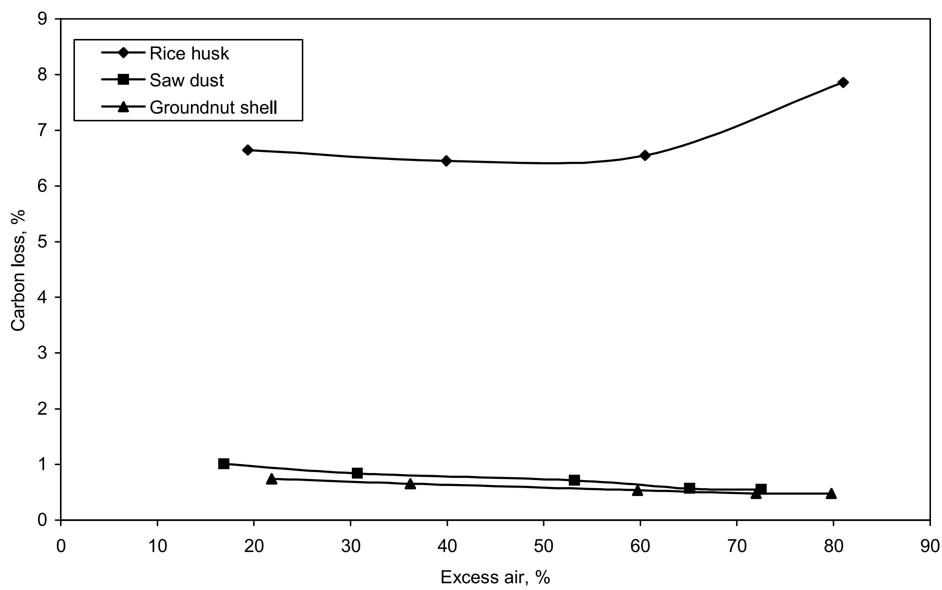


Figure 7. Effect of excess air on carbon carry over along with ash at cyclone separator for different biomass fuels.

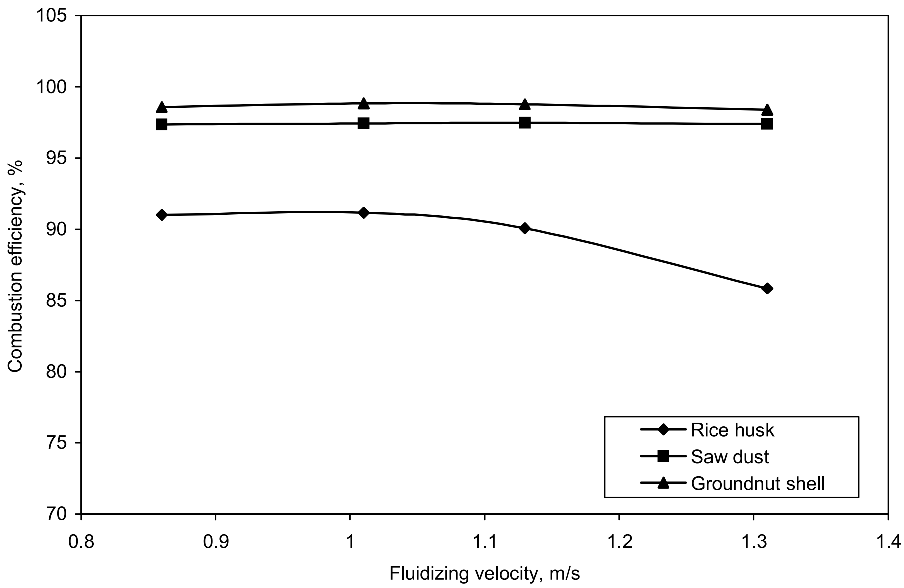


Figure 8. Effect of fluidizing velocity on combustion efficiency for different biomass fuels.

Effect of Operating Conditions on Combustion Efficiencies

Figure 8 shows the combustion efficiency for the selected fuels fired at maximum combustor loads for different fluidizing velocity. The maximum possible combustion efficiency with rice husk is observed to be 91.2% at fluidizing velocity of 1.0 m/s, and for sawdust and groundnut shells, combustion efficiencies are 97.4 and 98.8% at fluidizing velocity of 1.13 m/s. The combustion efficiency is much lower for rice husk because of higher carbon loss with increase in velocity of air. This behavior can be attributed to the facts that increase in fluidization velocity results in increase of unburned carbon content in the ash. Bhattacharya and Weizhang (1990) have reported the combustion efficiency of rice husk in the range of 81 to 98% and it is observed to increase with increase in the airflow rate. On the contrary, in the present investigation, the combustion efficiency of rice husk tends to decrease when the airflow rate is greater than 1.0 m/s.

When the excess air is supplied at the free board zone as secondary air, the combustion efficiencies are improved for all the fuels. From Figure 9 it can be observed that a reduction in combustion efficiency takes place after 60% of excess air with rice husk as fuel. Only a slight rise in combustion efficiencies is observed for sawdust and ground shells even though there is a considerable reduction of carbon losses because of low ash-fuel ratio. In the present work, the combustion efficiency of rice husk is increased up to 92%, due to a supply of excess air near the enlarged free board region.

Conclusions

The combustion of biomass fuels, i.e., rice husk, sawdust, and groundnut shell, has been studied in a laboratory scale fluidized bed combustor and combustion efficiencies are found to be between 90 to 99%. The excess air between 50 to 60% is found to be optimal in reducing carbon loss during the burning of the three distinct biomass fuels.

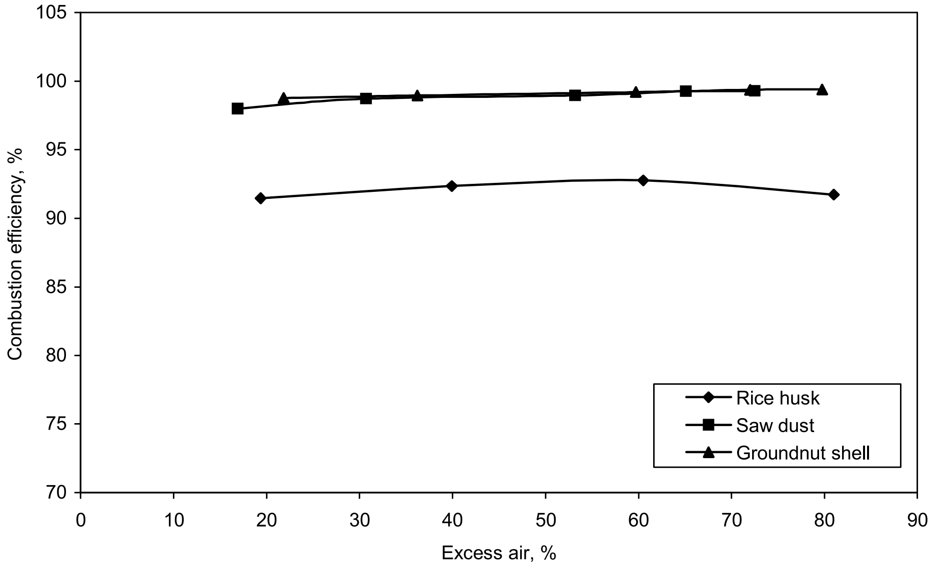


Figure 9. Effect of excess air on combustion efficiency for different biomass fuels.

There is a scope for combined burning of these fuels in a fluidized bed with a maximum possible conversion efficiency.

Acknowledgments

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, dated 6-6-2001).

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