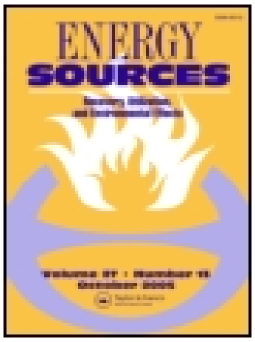

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Cold Flow Studies of Rice Husk, Saw Dust, and Groundnut Shell Fuels in a Fluidized Bed

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Abstract *Biomass is a low-grade energy source and must be upgraded for effective utilization of these residues as fuels. A fluidized bed technology permits a wide range of low-grade fuels of non-uniform size to be efficiently converted to other energy forms. Due to large density variations of fuel and inert solids in the bed, it is difficult to estimate hydrodynamic and mixing characteristics of the mixture in the bed. In the present work, three biomass fuels (i.e., rice husk, saw dust, and groundnut shells) are selected and their fluidization characteristics are estimated in the presence of sand bed. It is observed that, for good mixing and uniform distribution of biomass fuel with bed material, size of the sand particles plays a vital role and is found that the sand particles of mean diameter 0.66 mm for groundnut shells and sand particle size 0.44 mm for the other two fuels is best suited. The minimum fluidization velocity has been obtained from the experiential investigation for a fuel/sand two-component system and has been compared with the theoretical correlations available in the literature. A suitable correlation to determine the minimum fluidization velocity for the selected biomass fuels and sand mixture has been suggested.*

Keywords fluidized bed, groundnut shell, minimum fluidization velocity, mixing characteristics, rice husk, sawdust

Introduction

The potential of agricultural residues for energy production has been investigated by many researchers (Jenkins and Bhatnagar, 1991; Kjellstrom, 1993; Babu et al., 1995). Lepori et al. (1980) have suggested that fluidized bed energy technology offers several unique characteristics for using biomass in small-scale energy conversion operations. In the fluidization process, minimum fluidization velocity of the fluid bed is one of the important parameters that affects the suspension of bed material in the fluid stream. Although a number of theoretical correlations have been developed to estimate minimum fluidization velocity for different materials by many researchers, the suitability of these correlations to biomass fuels have not been studied (Leva, 1959; Todes, 1965; Kunii and Levenspiel, 1969; Chattopadhyay, 1996; Howard, 1983). Xu et al. (1985) and Flanigan et al. (1987) have indicated that minimum fluidization velocity of husk and sand mixture is approximately equal to terminal velocity (0.8 ms^{-1}) for sand particles of size 234 μm. Experimental investigations were also carried out to find minimum fluidization velocities for different biomass fuels and it has been concluded that the fluidizing velocities

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determined experimentally do not coincide with the theoretical values for most of the biomass residue fuels (Abdullah et al., 2003). There is also no agreement on the value of minimum fluidization velocity of biomass fuels from experimental findings of different researchers. Fang et al. (2004) has conducted experiments with rice husk as fuel material in a fluidized bed and found that the minimum fluidizing velocity of pure rice husk is about 0.60 ms^{-1}, which is a considerably high value when compared to 0.37 ms^{-1} found from the experimental results of Abdullah et al. (2003) for the same rice husk fuel. To improve fluidization behavior of rice husk silicon, sand and coal are added in a fluidized bed and respective operation gas velocity is found to be between 0.6 and 2.2 ms^{-1} (Fang et al., 2004).

Regarding solid mixing and segregation characteristics in a fluidized bed, it is found that the influence of particle size on segregation is not as much as the density difference (Ho et al., 1987; Bilbao et al., 1988; Hemati et al., 1990; Aznar et al., 1992). As the density difference between biomass fuels and inert solids is more in the fluidized bed, inappropriate mixing of solids takes place, which may adversely influence the combustion characteristics. In order to evaluate the influence of fluidization velocity on particle mix of binary system, different experiments were conducted and it is predicted that no segregation takes place at low fluidization velocities, considerable segregation at intermediate velocities, and vigorous mixing at large fluidizing velocities (Gera et al., 2004).

In this article, an attempt is made to demonstrate the affect of sand particle size on minimum fluidization velocity and mixing/segregation of the selected fuel-sand mixtures in an atmospheric bubbling fluidized bed, and the effect of fluidization velocity on mixing characteristics.

Material Preparation and Properties

In the present investigation, three biomass fuels (rice husk, sawdust, and groundnut shells) are used in the same condition as they are received without drying or sizing. The standard methods of determining fuel characteristics are given in Table 1. To find out fuel composition, proximate and ultimate analyses are carried out and the results are given in the Tables 2 and 3.

Experimental Setup and Experimentation

The experimental set up consists of a circular cross-section fluidized bed vessel with an internal diameter of 0.09 m and a height of 1.2 m, fabricated out of a 4-mm-thick

Table 1
Methods to determine properties of bed and fuel material

S. no.	Property	Method of testing
1	Sand and fuel particle size	IS: 460 (part I): 1985
2	Bulk density of sand	IS: 7190: 1974
3	True density of sand	IS: 1448: 1989
3	Preparation fuel sample	IS: 436 (part II): 1965
4	Bulk density of fuel	IS: 7190: 1974
5	True density of fuel	Abdullah et al., 2003

Table 2
Proximate analysis of fuels

Property	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 3
Ultimate analysis of fuels

Property	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
Sulphur, %	0.03	0.01	0.00

transparent acrylic resin tube. The distributor plate of straight orifice type is fixed at the bottom of the fluidization vessel for which the ratio of the total open area of the distributor to the cross sectional area is 0.0619. A mild steel distributor plate is designed as per the procedure adopted by Kunii and Lavenspiel (1969). Six pressure taps are located above the distributor along the axial length of the vertical tube at an equal interval of 135 mm to measure the pressure drop across the bed and one pressure tap is placed below the distributor to measure pressure drop across the distributor. A centrifugal blower is used to supply air and a throttle valve to regulate the flow rate. An orifice meter with D and D/2 tapings is designed to measure flow rate of air as per IS-14615 (Part 1): 1999. All the tests were conducted in such a way that no entrainment of fuel and sand particles takes place during fluidization operation.

To determine the suitable size of bed material for good mixing with the fuel particles, three different sizes of sand particles are chosen viz. 0.93, 0.66, and 0.4 mm. The characteristics of bed material are presented in Table 4. Initially, the sand with selected mean particle size is poured through the top of the vessel until it reaches the static bed

Table 4
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_s in kg m^{-3}	2,520	2,520	2,519
Bulk density, ρ_b in kg m^{-3}	1,500	1,520	1,600
Terminal velocity of the particle, U_t ms^{-1}	7.341	4.894	3.18
Static voidage, ε	0.4	0.392	0.36

Table 5
Properties of fuels

Property	Rice husk	Saw dust	Groundnut shell
Mean particle size, 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, kJ/kg	14,482	18,689	19,728

height of 30 mm. Fuel particles are then introduced above the sand bed to a total height of 60 mm. The properties of fuel particles are given in Table 5. Fluidized air is supplied through the distributor with a centrifugal-type blower. The flow rate of air is gradually increased and pressure drop across the bed as well as bed height from the distributor plate are measured. The experiments in each trial are carried out until the elutriation of the material from the bed starts.

In order to evaluate the mixing characteristics of fuel and sand, measured amounts of sand and fuel particles are added to the cold model fluidized bed and fluidized air is injected into the bed. The bed is operated above the minimum fluidization velocity for more than 900 s duration and thereafter the supply of air is stopped suddenly. Then the bed is divided into four equal quarters and the mixture of fuel and sand in every section is taken out and is sieved through a set of standard sieves to separate fuel and sand. Then the fuel and sand collected from each section are weighed separately to obtain the mass fractions. These experiments are carried out for all three fuels and mass fractions, X_{ri}, X_{si}, and X_{gi}, of rice husk, sawdust, and groundnut shells are determined.

Results and Discussion

Minimum Fluidization Velocity

M_r is taken as the mean mass proportion of rice husk to sand in the rice husk/sand two-component system. Similarly, M_s and M_g are taken as mean mass proportion of sawdust and groundnut shells, respectively. For the present study, M_r, M_s, and M_g are 1:13, 1:5, and 1:12, respectively. The plot of pressure drops Δp against the superficial velocity U for rice husk is shown in Figure 1. The minimum fluidization velocities for the sand particle of size 0.93, 0.66, and 0.4 mm have been observed at 0.54, 0.5, and 0.48 ms^{-1}, respectively. It is clear that the minimum fluidization velocity is low when sand has a mean diameter of 0.4 mm and, hence, it is more suitable for fluidization of rice husk. But there is not much agreement in the minimum fluidization velocity value obtained by previous investigators (Abdullah et al., 2003; Fang et al., 2004) for the rice husk and sand mixture. The reasons for the variation in results could be due to the difference in mass ratio of rice husk to sand, particle size distribution, type of distributors, and static bed height.

Figure 2 shows the variation of pressure drop against fluidizing velocity of saw dust and sand mixture. When the bed is fluidized with sand of size 0.93 mm, channeling has been observed which is indicated by low-pressure drop profile. This is an abnormality characterized by the establishment of flow paths in a bed of solids through which large amounts of fluid pass up the column. As the size of the sand is decreased, the normal pressure drop profile is observed; therefore, 0.4 mm sand particle size has been found to

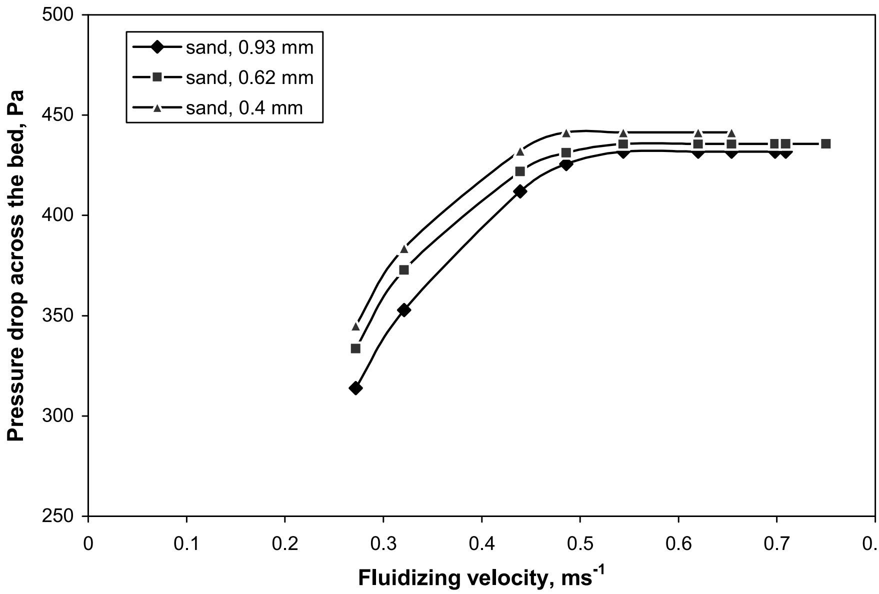

Figure 1. Variation of pressure drop across the bed against fluidizing velocity for the rice husk and sand mixture (M_r, 1:13).

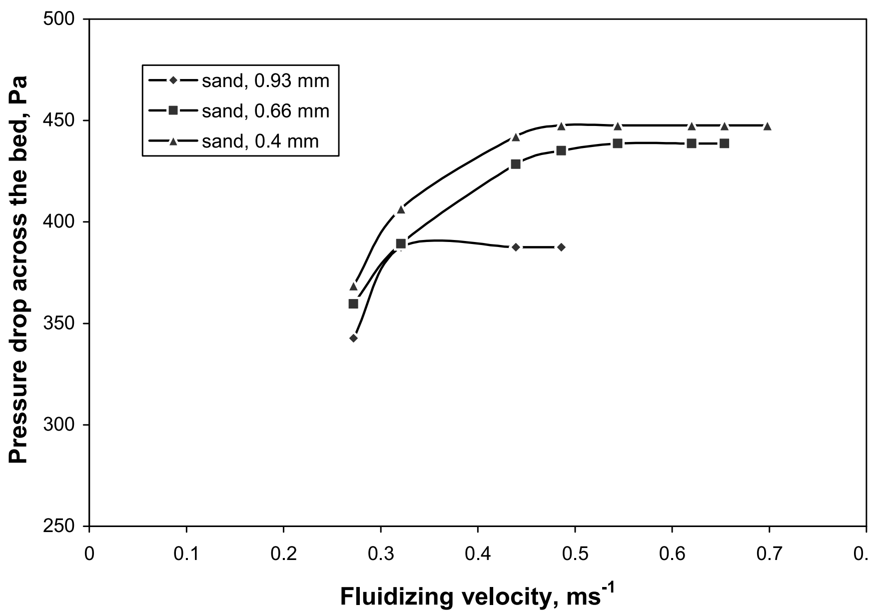

Figure 2. Variation of pressure drop across the bed against fluidizing velocity for the sawdust and sand mixture (M_s, 1:5).

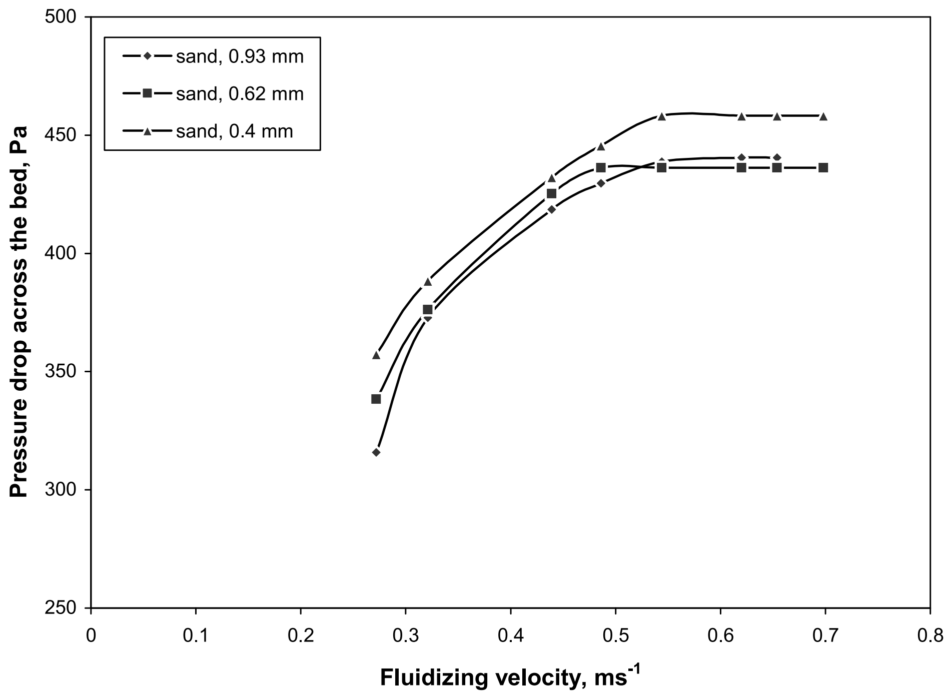

Figure 3. Variation of pressure drop across the bed against fluidizing velocity for groundnut shells and sand mixture (M_g, 1:12).

be more appropriate for the fluidization of sawdust. The minimum fluidization velocity has been observed to be the lowest for the particle size of 0.66 mm (i.e., 0.48 ms^{-1} with groundnut shells as shown in Figure 3).

All three fuels are found to elutriate out of the bed when the fluidizing velocity is greater than 0.65 ms^{-1}. Thus, the operating gas velocity in the fluidized bed should be between 0.48 and 0.65 ms^{-1}.

Comparison of Theoretical and Experimental Minimum Fluidization Velocity

Correlations developed by different investigators are used to calculate the theoretical minimum fluidization velocity and are presented in Table 6. From Table 6 it has been found that the minimum fluidization velocity obtained from equation $\mathrm{Re}_{mf} = \frac{Ar}{18+5.22\sqrt{Ar}}$ proposed by Todes (1965) is closer to the experimental value. The same equation is also applied for other particle sizes and reasonable agreement is found as shown in Table 7.

Mixing Characteristics

Proper mixing of fuel and sand particles play a vital role for stable combustion in a fluidized bed. The mixing characteristics of the selected fuel and sand mixture are shown in Table 8. It could be seen that the mass fraction of rice husk in four different sections is more irregular with sand of sizes 0.93 and 0.66 mm, whereas mass fraction of rice husk with sand of size 0.4 mm is nearly constant in all the sections. Therefore, sand with

Table 6
Theoretical determination of minimum fluidization velocity

S. no.	Correlation for minimum fluidization velocity, U_{mf}	U_{mf}, ms^{-1}	Reference
1	$\mathrm{Re}_{mf} = \frac{Ar}{150\left(\frac{1-\varepsilon_{mf}}{\varepsilon_{mf}^3}\right)+\sqrt{\frac{1.75Ar}{\varepsilon_{mf}^3}}}$	0.233	Howard (1983)
2	$\mathrm{Re}_{opt} = \frac{Ar}{18+5.22\sqrt{Ar}}$	0.53	Todes (1965)
3	$\mathrm{Re}_{mf} = \frac{Ar}{1400+5.22\sqrt{Ar}}$	0.12	Chattopadhyay (1996)
4	$\mathrm{Re}_{mf} = [(28.7)^2 + 0.0494\,Ar]^{0.5} - 28.7$	0.174	Kunni and Levenspiel (1969)
5	$U_{mf} = \frac{9.4\times10^{-4}(\rho_p-\rho_g)^{0.934} g^{0.934} d_p^{1.8}}{\mu^{0.87}\rho_g^{0.066}}$	0.12	Leva (1959)
6	$U_{mf} = \{[Ly]_{mf}\mu\rho_p g/\rho_g^2\}^{1/3}$	0.29	Chattopadhya (1982)
7	From the experimentation with sand rice husk mixture for sand particle size of 0.4 mm (Figure 1)	0.48	Present work

Reynolds number at minimum fluidization state $= \mathrm{Re}_{mf} = \left(\frac{d_p U_{mf}\rho_g}{\mu}\right)$ and Archimedes number $= Ar = \frac{d_p^3\cdot\rho_g(\rho_s-\rho_g)\cdot g}{\mu^2}$.

the mean diameter of 0.4 mm is found to mix well with rice husk. The phenomenon of segregation is serious when the other sizes of sand particle are chosen as bed materials.

In the case of sawdust, when 0.93 mm sand size is used, it is observed that the maximum amount of sawdust is collected in one section only due to a channeling effect. In the remaining sections, a considerably small amount of fuel material is noticed. This effect of channeling is not found with a decrease in particle size and it is observed that

Table 7
Comparison of experimental minimum fluidization velocity with the correlation proposed by Todes (1965)

S. no.	Fuel	Mean particle size of sand, mm	Theoretical, U_{mf}, ms^{-1}	Experimental, U_{mf}, ms^{-1}
1	Rice husk	0.93	0.82	0.54
2	Rice husk	0.66	0.69	0.5
3	Rice husk	0.4	0.53	0.48
4	Saw dust	0.66	0.69	0.54
5	Saw dust	0.4	0.53	0.48
6	Groundnut shells	0.93	0.82	0.62
7	Groundnut shells	0.66	0.69	0.48
8	Groundnut shells	0.4	0.53	0.54

Table 8
Mixing characteristics of fuels with bed material sand

Size of the sand particles in the bed, mm	Percentage of mass fraction of fuel in each quarter, X_{ri}, X_{si}, X_{gi}											
	Rice husk—M_r, 1:13, required mass fraction in each quarter—X_r, 6.7%				Saw dust—M_s, 1:5, required mass fraction in each quarter—X_s, 15.44%				Groundnut shell—M_g, 1:12, required mass fraction in each quarter—X_g, 7.19%			
	X_{r1}	X_{r2}	X_{r3}	X_{r4}	X_{s1}	X_{s2}	X_{s3}	X_{s4}	X_{g1}	X_{g2}	X_{g3}	X_{g4}
0.4	7.28	5.88	6.36	7.31	16.36	16.08	15.08	14.25	7.4	6.9	6.2	8.3
0.66	7.1	4.12	9.2	6.38	15.4	17.8	18.9	9.65	7.22	7.34	7.41	6.8
0.93	7.15	3.4	6.32	9.96	49.71	8.6	3.47	0	7.5	6.4	6.2	8.7

when 0.4 mm sand size is used as bed material, the mass fraction of sawdust is almost constant in all the sections.

The mass fraction of groundnut shells during mixing with different size of sand particles is fairly good in all the cases and among the three different sizes of sand particles 0.66 mm size is observed to have better mixing with groundnut shells.

Effect of Fluidizing Velocity on Mixing of Fuel Particle with Sand

The influence of fluidizing velocity on mixing of fuel particles can be explained with the help of bed expansion measured during the fluidization process. Above the minimum fluidization velocity of sand and fuel mixture, a considerable bed expansion is observed. Owing to their low density, the bed expansion of fuel particles is observed to be greater when compared with sand particles. The bed expansion against fluidizing velocity for rice husk is shown in Figure 4. As the fluidizing velocity increases, initially the bed

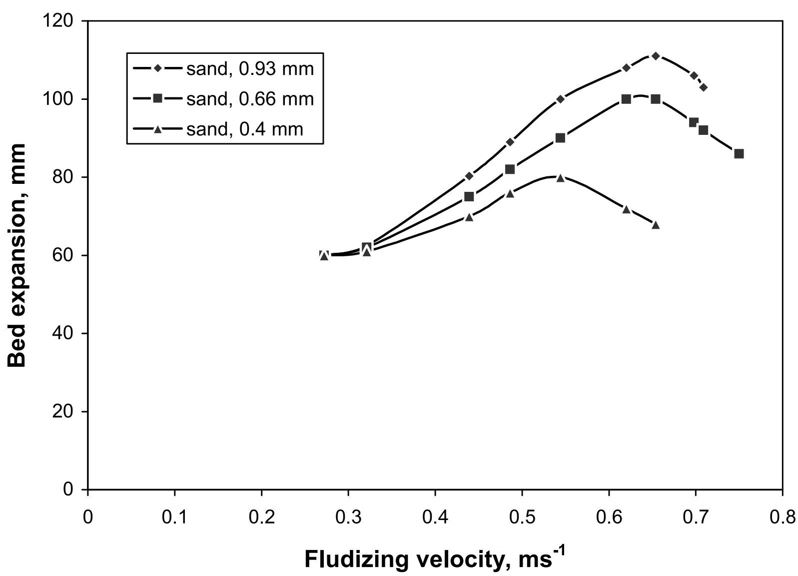

Figure 4. Effect of fluidizing velocity on bed expansion for rice husk and sand mixture (M_r, 1:13).

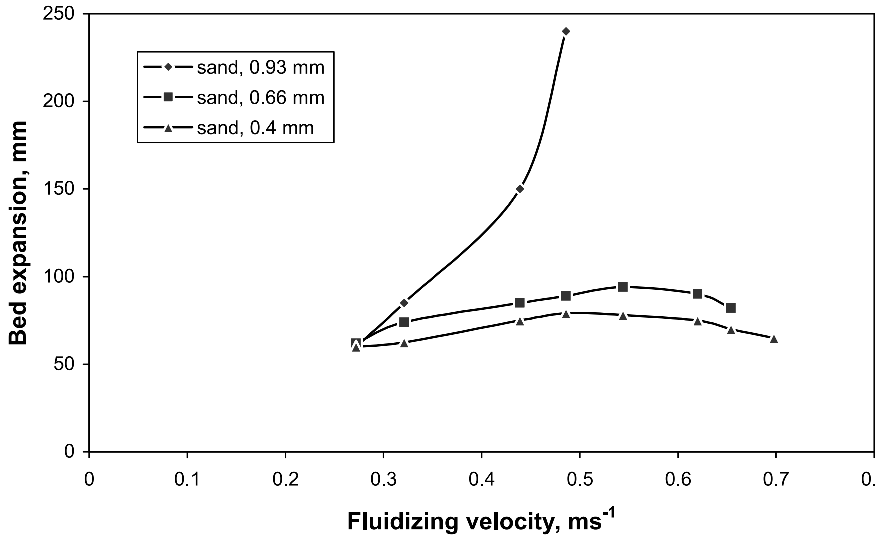

Figure 5. Effect of fluidizing velocity on bed expansion for sawdust and sand mixture (M_s, 1:5).

height increases, and thereafter, there is a reduction in the bed height because of internal circulation of rice husk particles. This phenomenon is observed with all three sizes of sand particles. The lowest bed heights are noticed for a sand of size 0.4 mm in the case of rice husk and sawdust and 0.66 mm in the case of groundnut shells indicating better mixing of fuel with sand as shown in Figures 4–6, respectively.

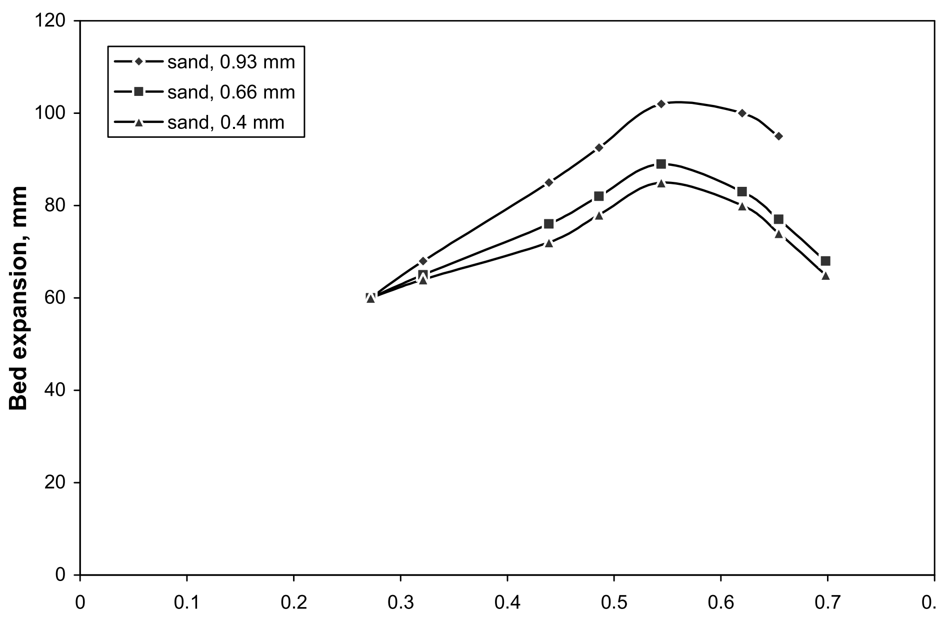

Figure 6. Effect of fluidizing velocity on bed expansion for groundnut shells and sand mixture (M_g, 1:12).

Conclusions

- The selection of appropriate size of sand is most important for good fluidization of sand and fuel mixtures. It is observed that separate experimental investigations are necessary to evaluate the exact hydrodynamic parameters for each fuel and sand mixture.
- It is found that effect of particle size of sand on mixing characteristics is more prominent for sawdust. On other hand, the groundnut shells are found to mix moderately with any of the three selected sizes of sand and have little influence on the particle size.
- It is evident from the experiments that with increase in fluidizing velocity better mixing can be achieved without any segregation.
- The equation proposed by Todes (1965) is most suitable to estimate the theoretical minimum fluidization velocities for different biomass fuels.

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Nomenclature

A	bed cross sectional area, m^2
Ar	Archimedes number, $\frac{g\rho_g(\rho_p-\rho_g)D_p^3}{\mu^2}$
d_p	diameter of the particle, m
d_{or}	diameter of orifice in the distributor plate, m
g	acceleration due to gravity, m s^{-2}
L_{mf}	length of bed at minimum fluidization, m
L_s	length of static bed, m
$[\mathrm{Ly}]_{mf}$	Lyaschenko number at minimum fluidization state
M_g	mean mass proportion of groundnut shell in the mixture of sand and groundnut shell
M_r	mean mass proportion of rice husk in the mixture of sand and rice husk
M_s	mean mass proportion of saw dust in the mixture of sand and saw dust
N_o	Number orifices in the distributor plate
Re_{mf}	Reynolds number at minimum fluidization
U	superficial velocity of air, m s^{-1}
U_{mf}	minimum fluidization velocity, m s^{-1}
U_o	fluidization velocity through orifice of distributor plate, m s^{-1}
W	weight of the bed, kg
X_{gi}	mass fraction of groundnut shell in sand and groundnut shell mixture, %
X_{ri}	mass fraction of rice husk in sand and rice husk mixture, %
X_{si}	mass fraction of sawdust in sand and saw dust mixture, %

Greek Letters

ε	bed voidage
ε_{mf}	bed voidage at minimum fluidization
μ	gas viscosity, N s m^{-2}
ϕ	sphericity
ρ_m	density of manometric fluid, kg m^{-3}
ρ_g	fluid or gas density, kg m^{-3}
ρ_s	density of sand, kg m^{-3}
Δh	difference in height between manometric limbs, m
Δp	pressure drop across the bed, N m^{-2}
Δp_d	pressure drop across the distributor plate, N m^{-2}