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Some studies on wall-to-bed heat transfer in a pressurized circulating fluidized bed unit

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Abstract

In the present work, a pressurized circulating fluidized bed (PCFB) unit of 54 mm inner diameter and riser height of 2000 mm has been fabricated to investigate the effect of pressure on suspension density and heat transfer. The effects of blending of biomass in sand, and superficial velocity on bed hydrodynamics and heat transfer has also been studied. Experiments have been conducted at four different percentage blending of biomass such as 2.5 %, 7.5 %, 15 % and 20 % in sand with two different weight composition ratios and at a superficial velocity of 5 m/s. Operating pressure is varied from 1 to 5 bar in a step of 2 bar. Results show that, the axial heat transfer coefficient increases from the bottom to the top of heat transfer probe with the increase in operating pressure. The radial variation of heat transfer coefficient decreases from the wall to the core of the heat transfer probe. The heat transfer coefficient is also found to be higher in between the 7.5 to 15 % biomass blending in sand. The overall uncertainty in calculating heat transfer coefficient is found to be 3.90 %.

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Keywords: Circulating fluidized bed; heat transfer coefficient; operating pressure; bed voidage; suspension density.

Nomenclature

A_B	Cross sectional area of the bed in m^2
A_D	Cross sectional area of downcomer in m^2
A_{htp}	Surface area of heat transfer probe in m^2
G_s	Solid circulation rate in kg $m^{-2}s^{-1}$
h	Heat transfer coefficient
Δh	difference of height in manometric fluid measured in cm of water column
I	Supply current
L_a	Solid accumulation height in m
L_m	Difference between two consecutive pressure taps
q	Heat flux
t	Time to accumulate particular height after closing ball valve in sec
T_{bi}	Bed temperature in K

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T_{bs}	Bulk surface temperature in K
U_{sup}	Superficial velocity in m/s
B/S	Biomass (sawdust) to sand ratio
V	Supply Voltage
Greek symbols	
ρ_g	Gas density in kg/m^3
ρ_s	Solid density in kg/m^3
ρ_{sus}	Suspension density in kg/m^3
ε	Bed voidage
ε_{mf}	Bed voidage at minimum fluidization

1. Introduction

Circulating fluidized bed (CFB) has emerged as an environmentally acceptable technology for burning wide range of solid fuels to generate steam and electricity with improved plant efficiency. Pressurized circulating fluidized bed (PCFB) is the second generation technology which is still in the pilot scale level. Extensive research on the design and various parameters influencing the performance of a PCFB is in progress, both in industrial and academic level because of its unique advantages such as compactness, fuel flexibility and higher efficiency apart from in-situ capture of SO_2 and NOx [1-3]. As compactness is an important feature of PCFB boiler, the heat transfer plays an important role in design and operation of a PCFB boiler. The performance of a PCFB unit is influenced by a number of factors, including superficial velocity, solid circulation rate, solid inventory, and particle size distribution. The effect of these operating parameters was studied by various researchers [1-3]. Change of any of these parameters changes the bed hydrodynamics such as bed voidage, suspension density etc. and this causes a change in the heat transfer along the bed height. The knowledge of bed hydrodynamics at varied pressure condition is very essential in designing and optimization of PCFB components. Many researchers have reviewed the bed hydrodynamics and heat transfer at atmospheric conditions [3-6]. At present, not much information is reported on PCFB riser hydrodynamics and on cluster characteristics length and residence time. Some of the reported literature related to bed hydrodynamics and its effect on heat transfer is discussed in the following subsections.

The effect of hydrodynamic parameters, pressure and temperature on bed-to-wall heat transfer coefficient was studied by Reddy and Basu [7]. Gungor and Eskin [8], developed a two dimensional model considering the hydrodynamic behavior of CFB to investigate the effect of superficial velocity on bed hydrodynamics. Gupta and Nag [1], reported that, with the increase in superficial velocity, the bed voidage increases in the bottom portion and decreases in the top region as more solids are lifted up due to more drag force in a PCFB. The concentration of sand particles is more in the riser column for higher bed inventory, and hence, the bed voidage is lower. Reddy and Knowlton [9], investigated the effect of operating pressure on CFB riser hydrodynamics in a 300 mm diameter tube. The result obtained was contradictory to those obtained by Plasynski *et al.,*[10]. The difference was attributed to higher gas pressure drop in the smaller tube compared to the larger diameter tube. It is also observed that the pressure drop due to gas density is inversely proportional to diameter raised to the power of 1.25. Richgerg *et al.* [11], conducted some experimental investigations in a 0.19 m diameter and 9 m high pilot scale PCFB unit in order to characterize the flow patterns in a PCFB. The obtained information is used to develop an easy correlation for the prediction of internal solids reflux in a riser reactor as a function of solids/gas density ratios and the dimensionless superficial gas velocity. It is reported that, the local voidage, and the gas and solid velocities change continuously from the axis to the wall [12-15]. The voidage is highest along the axis of the riser column and lowest in the wall which is observed by various researchers [3, 14, 16]. The radial voidage distribution is much flatter in the upper section of the bed, as well as at lower circulation rates. In case of fast fluidized beds, there is a gas-solid boundary layer, where the solid generally moves downward. This is investigated that for both in large commercial boilers as well as in laboratory units [16-17]. Yue *et al*., [18] suggested that by changing the bed inventory, one can influence the suspension density. As commented by Li and Kwauk [19], and Kunii and Levenspiel [20], the suspension density along the height of a CFB boiler varies exponentially as it does in the freeboard region of a bubbling fluidized bed. However, Andersson and Leckner [21], and Brereton and Stromberg [22] found that, the profile to be better represented by a power-law equation. Yates [23] reviewed the effect of pressure and temperature on fluidized bed and emphasized that more effort needs to be devoted to CFB's as there are many gaps in understanding the flow regime that exist in these system. Wu *et al.* [24] and Ebert *et al.* [25] suggested that, except for a very dilute bed, the superficial gas velocity does not have any great influence on the heat transfer coefficient. It is a result of a relatively low contribution of the gas convection component. In some situations, the heat transfer coefficient at constant circulation rate even decreases with the increase of superficial velocity due to the resulting decrease in the suspension density [25-27]. Divillo and Boyd [28], show a major effect of superficial velocity but a minor effect of suspension density on the heat flux. Various researchers [1, 3-6] suggested that, the heat-transfer coefficient in a CFB riser increases from the bottom to the top and is influenced by a number of factors, including air flow, solid circulation rate, solid inventory, and particle size distribution. Basu [3] emphasized that, the major effect of these parameters on the heat transfer is due to their influence on the suspension density. Glicksman [29] studied the effect of heat transfer coefficient and its dependency on suspension density. It is concluded that, the heat transfer coefficient is found to vary as square root of the cross-section average suspension density. Divilio and Boyd [28], presented an overview of the effect of suspension density on the heat transfer using the data from the laboratory, pilot plants, and operating plants. They observed that, the suspension density varies with the height of the riser. As the combustor gets taller, the solid suspension density decreases further, resulting in lower heat transfer coefficients. Gupta and Nag [1], studied the bed to wall heat transfer behavior in a 37.5 mm ID and 1940 mm height PCFB riser where the heat transfer coefficient was found increasing with an increasing operating pressure as well as with an increase in gas superficial velocity. It was also observed that, with the increase in pressure, the bed voidage increased in the bottom zone of the riser and decreased in the top zone, thereby increasing the suspension density at the top zone. Recently, similar observations have been made by Kalita *et al.* [30]. In the book written by Oka and Oka [31], it is reported that 12 % biomass blending in sand in the case of bubbling fluidized bed found to be optimum for maximum heat transfer and proper gasification. Although much work has been done on the effect of various operating parameters on heat transfer associated with the CFB, it is very essential to study the operating parameters on the PCFB. Besides, study related to the blending of biomass in sand at varied proportions is a challenge for optrimization of a gasification and combustion process. In the present investigation, the effects of blending of biomass in sand on bed hydrodynamics and heat transfer at varied operating pressures in a pressurized circulating fluidized bed has been studied.

2. Materials and method

2.1 Setup description

The schematic diagram of the pressurized circulating fluidized bed (PCFB) setup is shown in Fig.1. A photograph of the setup is shown in the Fig.2. The PCFB unit comprises of a riser, a transparent downcomer, and a cyclone separator. The riser is made of stainless steel of ID 54 mm and height of 2000 mm. Air is supplied to the CFB unit through the bottom of the riser by a high pressure centrifugal blower and a compressor. The air flow rate is measured by a standard orifice meter and is regulated by an air control valve and a bypass arrangement. The air passes through a porous distributor plate (straight hole) of 16.8 % opening area which is fixed at the bottom of the riser column. The entrained solids goes out of the riser are recovered in a cyclone separator and are then sent to the bottom of the riser column through a transparent return leg of ID 24.5 mm. Static pressures and hence voidage were measured along the riser height at 6 (six) different locations such as 120 mm, 192.5 mm, 370 mm, 495 mm, 970 mm and 1570 mm above the distributor plate. Suspension densities at those points were also calculated. Fine wire mesh (200 μm) and cigarette filters are used at the pressure taping ends to minimize the pressure fluctuations and to avoid the escape of sand particles from the column. Pressure drops are measured with U-tube water filled manometer fabricated for this purpose. The heat transfer probe of height 500 mm is located at a height of 1300 mm above the distributor plate i.e. at the upper splace region of the riser. Necessary thermocouples are facilitated to measure the surface and bed temperatures. The locations of the thermocouples from the distributor plate are 1400, 1500, 1600, 1700 and 1800 mm. Besides, thermocouples are also installed to measure the radial temperature variations in the bed at d/D of 0.2, 0.3, 0.4, 0.6 and 0.8. A heater coil (rated 1000 Watt and resistance 46 Ohms) of the required length is wrapped uniformly around the probe. Adequate electrical and thermal insulation are provided. Mica sheet of 1 mm thickness is used as electrical insulation over which heater coil is warped. For thermal insulation, ceramic wool and ceramic rope is used around the probe. The axial heat loss by conduction is also prevented by providing ceramic wool insulation in between the joints. Both surface and bed temperatures are measured with chromal-alumal thermocouples and these have been calibrated before use. Agilent 34972 LXI data acquisition/ switch unit is used for measurement and record of temperature.

2.2 Experimental procedure

A measured quantity of inventory is fed into the unit through the top of the cyclone separator and rests on the ball valve of the transparent return leg (downcomer) till the valve open. The heat transfer probe is heated by providing a known heat flux before the start of experiment. High precision pressure gauge (Swegelock make) is used for the measurement of the compressor delivery pressure. Blower delivery air flow is controlled by a gate valve installed along the flow, and the flow rate is calculated by measuring the orifice pressure drop (D and D/2 tapings) in the U-tube water manometer. Finally, the superficial velocity is calculated by using the measured orifice pressure drop. In each experiment, controlled amount of air is supplied from the blower at a required superficial velocity to the CFB loop. Compressed air is supplied from the compressor at a required pressure to the riser bottom. For each operating conditions, about 60 minutes time is required to attain the thermal and hydrodynamic equilibrium. For thermal equilibrium, temperature rise is monitored, and for hydrodynamic equilibrium, circulation rate is monitored. Once the equilibrium condition is reached, experimental data such as temperature, pressure drop and circulation rate are recorded in a data sheet for further analysis. Same procedure is followed with every change in operating parameters. Experiments were performed at a constant heat flux of 830 W/m^2 and at a superficial velocity of 5 m/s. The axial and radial variation of heat transfer coefficient with four proportions blending of sawdust in sand such as 2.5 %, 7.5 %, 15 % and 20 % have been studied and compared. Comparisons were also made at two different sets of weight composition ratios one of which is weight composition of sawdust with 400 gm sand and the other is weight composition of sawdust with 600 gm of sand. The percentage blending of sawdust is kept constant irrespective of weight compositions. All the experiments were conducted at three different system pressures of 1, 3 and 5 bar. Average particle size of sawdust and sand used for the experiment is calculated to be 407 μm and 309 respectively. Finally, bed hydrodynamics (bed voidage, suspension density and solid circulation rate) and heat transfer characteristics (axial and radial) were investigated. All the experiments were repeated thrice in order to establish the repeatability.

2.3 Working formula

For the axial probe, the wall-to-bed heat transfer coefficient is estimated from the measured local surface to bed temperatures as given below

$$h_\mathrm{i} = \frac{q}{A_\mathrm{htp}\left(T_\mathrm{bs} - T_\mathrm{bi}\right)} = \frac{V \times I}{A_\mathrm{htp}\left(T_\mathrm{bs} - T_\mathrm{bi}\right)} \tag{1}$$

where i, represents any location along the riser height and A_htp, is the heat transfer probe surface area. T_bs and T_bi are bulk surface temperatures and bed temperatures ,respectively.

The ***suspension density*** of the bed (ρ_sus) can be evaluated by the equation (Kunni and Levenspiel [20])

$$\rho_\mathrm{sus} = \rho_\mathrm{s}\left(1-\varepsilon\right) + \varepsilon\rho_\mathrm{g} \tag{2}$$

where voidage (ε) is defined as the volume fraction of the bed occupied by air bubbles, and ρ_g is the density of air in kg/m^3.

Voidage (ε) may be calculated by using the following expression,

$$\varepsilon = 1 - \frac{10 \times \Delta h}{\rho_\mathrm{s} \times L_\mathrm{m}} \tag{3}$$

where Δh is the difference of height in manometric fluid measured in cm of water column, L_m is the difference between two consecutive pressure taps across which pressure drops, and ρ_s is the density of sand in kg/m^3.

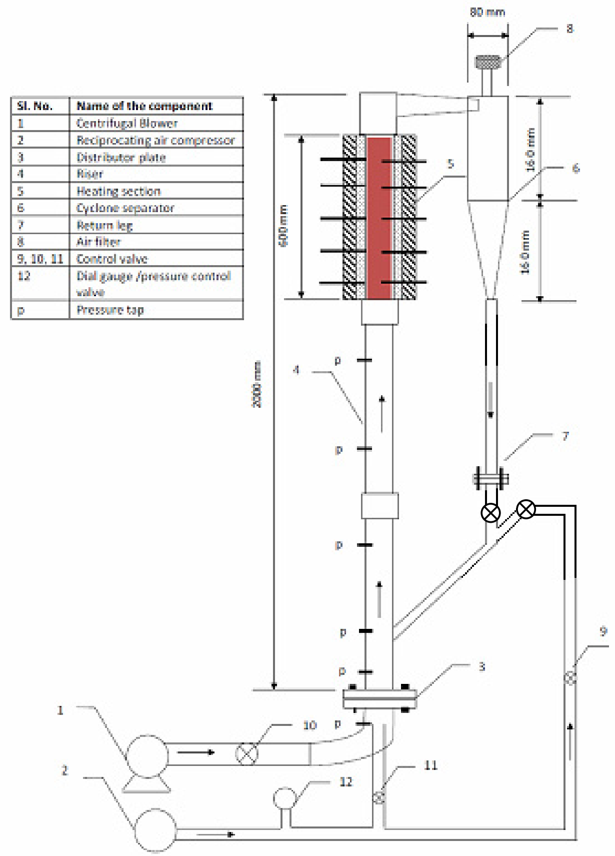
Solid circulation rate or solid mass flux (G_s) is given by,

$$G_\mathrm{s} = \frac{\rho_\mathrm{s} \times L_\mathrm{a} \times A_\mathrm{D} \times \left(1-\varepsilon_\mathrm{mf}\right)}{A_\mathrm{B} t} \tag{4}$$

3. Results and discussion

Figures 3 through 5 present the variation and comparison of bed voidage at operating pressures of 1, 3 and 5 bar. The comparisons were made at two different weight composition ratios and at a superficial velocity of 5 m/s. In these conditions percentage blending of biomass is maintained at 15%. As observed, the bed voidage is first decreases and then increases, before it decreases at the exit of the riser which may be better represented by S-shaped bed voidage profile. With the increase of pressure, the bed voidage decreases at the exit of the riser, this may be due to the increase in concentration of particles at the riser exit. This is observed to be more in the case of weight composition ratio of 90:600.

The variation of heat transfer coefficient at a height of 1.6 m from the distributor plate at 2.5 %, 7.5 %, 15 % and 20 % blending is shown in the Figs.6 through 9. The comparisons were made at two different weight composition ratios and at a superficial velocity of 5 m/s. From these figures it has been observed that, the heat transfer coefficient increases with the increase in operating pressures. The heat transfer coefficient is found to be higher (120-135 W/m^2-K) at 7.5 % blending (Fig.7) with weight composition ratio of 30 gm: 400 gm as compared to the other three percentage blending. The heat transfer coefficient is found to be lowest (90-105 W/m^2-K) at 20 % biomass blending (Fig.9) in comparison to the other blending at the superficial velocity of 5 m/s. This may be due to the lowest solid circulation rate observed in both the cases as compared to the other percentage blending. The values of the solid circulation rate at three different operating pressures and at four different % blending of sawdust at the superficial velocity of 5 m/s is shown in the table-1.



Sl. No.	Name of the component
1	Centrifugal Blower
2	Reciprocating air compressor
3	Distributor plate
4	Riser
5	Heating section
6	Cyclone separator
7	Return leg
8	Air filter
9, 10, 11	Control valve
12	Dial gauge /pressure control valve
p	Pressure tap

Fig.1. Schematic of experimental setup

Fig.2. Photograph of the experimental setup

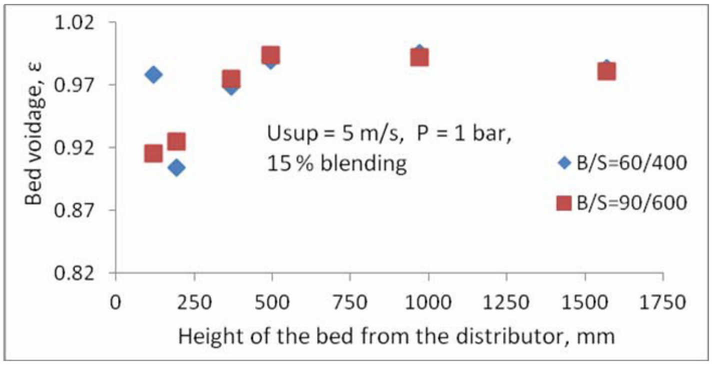


Fig.3. Variation of bed voidage along the height of the riser at P = 1 bar

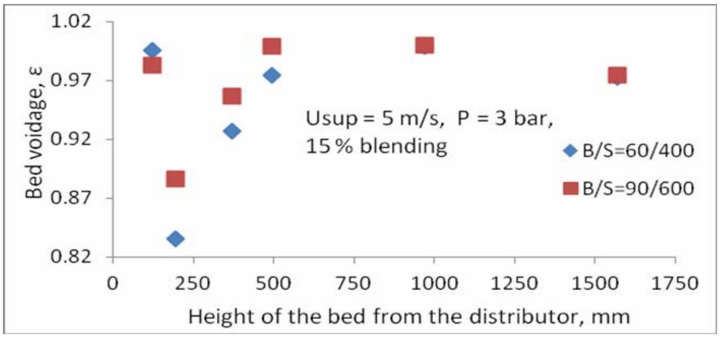


Fig.4. Variation of bed voidage along the height of the riser at P = 3 bar

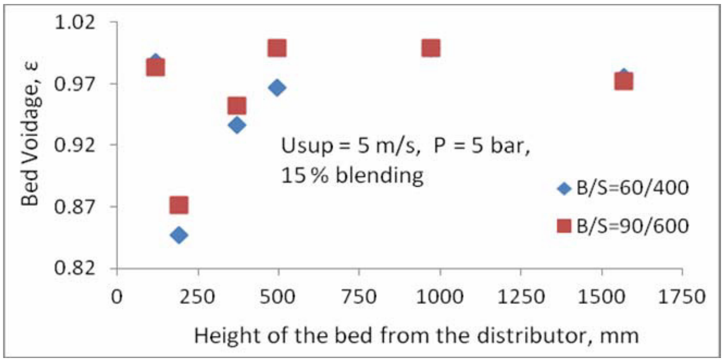


Fig.5. Variation of bed voidage along the height of the riser at P = 5 bar

Figure 10 show the variation of heat transfer coefficient along the heat transfer probe at the operating pressure of 5 bar and at the superficial velocity of 5 m/s. It is observed that, the heat transfer coefficient increases from the bottom to the top of the heat transfer probe. This is a representative figure for percentage blending of biomass in sand at varied pressure conditions. The similar variation of heat transfer coefficient without blending of biomass is demonstrated by Gupta and Nag [1]. The suspension density variation at a height of 1.57 m from the distributor with operating pressures at the superficial velocities of 5 m/s is shown in the Fig.11. The comparison is made at a percentage blending of 15 % and at two different weight composition ratios. It has been observed that, the suspension density increases with the increase in operating pressure in both the weight composition ratios. However, the higher values of suspension density have been observed at the weight composition ratio of 90 gm: 600 gm.

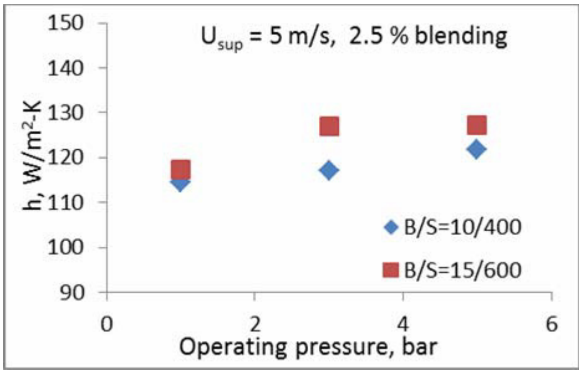


Fig.6. Variation of heat transfer coefficient at 2.5 % blending

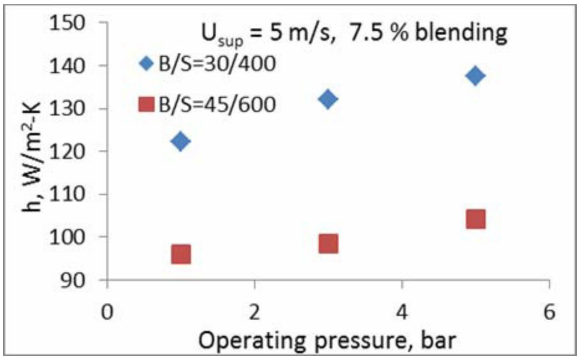


Fig.7. Variation of heat transfer coefficient at 5 % blending

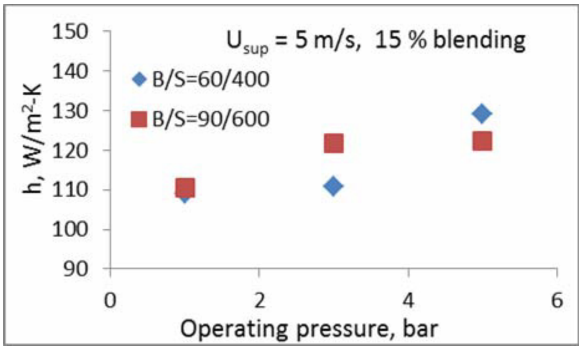


Fig.8. Variation of heat transfer coefficient at 15 % blending

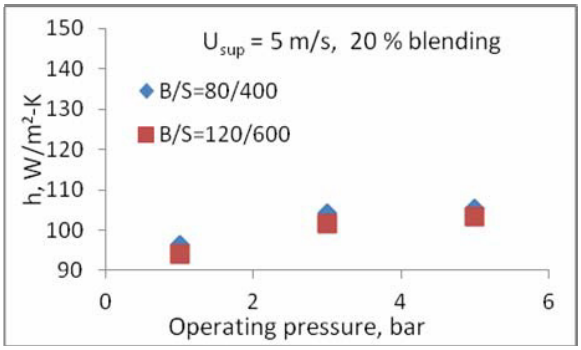


Fig.9. Variation of heat transfer coefficient at 20 % blending

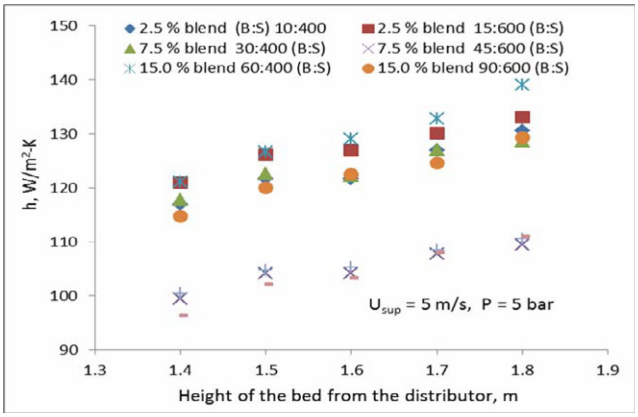


Fig.10. Comparison of variation of heat transfer coefficient along the heat transfer probe

Table 1. Solid circulation rate, G_s (kg $m^{-2}s^{-1}$) data with pressure

Pressure in bar	**2.5 % blend**		**7.5 % blend**		**15.0 % blend**		**20.0 % blend**	
	(B/S) 10:400	(B/S) 15:600	(B/S) 30:400	(B/S) 45:600	(B/S) 60:400	(B/S) 90:600	(B/S) 80:400	(B/S) 120: 600
				U_{sup} = 5 m/s				
1	0.816	1.381	0.946	1.072	0.773	0.912	0.205	0.0817
3	1.164	1.086	1.623	0.753	1.094	1.762	0.926	0.1388
5	0.9517	1.455	1.798	1.350	1.637	1.327	0.989	0.3033

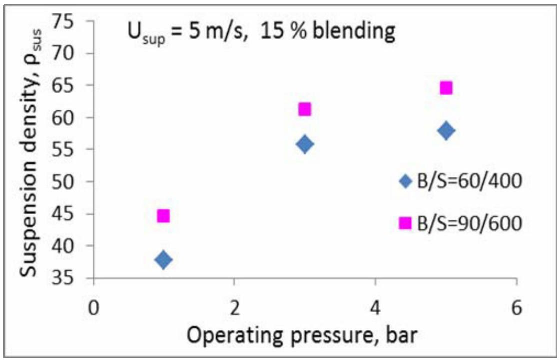


Fig.11. Variation of suspension density at U_{sup} = 5 m/s

The comparison of radial variation of heat transfer coefficient at two different % blending of sawdust such as 2.5 % and 15 % is shown in the Figs.12 and 13. These plots have been made at a distance of 1.6 m from the height of the distributor. From these figures it has been observed that, the heat transfer coefficient decreases from the wall to the core of the riser. This may be due to decrease in particle concentration from the wall to the core of the riser. It is also observed that with the increase in pressure, heat transfer coefficient increases. This may be due to the increase in particle concentration with increase in pressure. At 20 % biomass blending heat transfer coefficient near to the wall of the riser is found be highest and at the core it is found to be lowest. This is probably due to the diffusion of particles from the core to the wall of the riser.

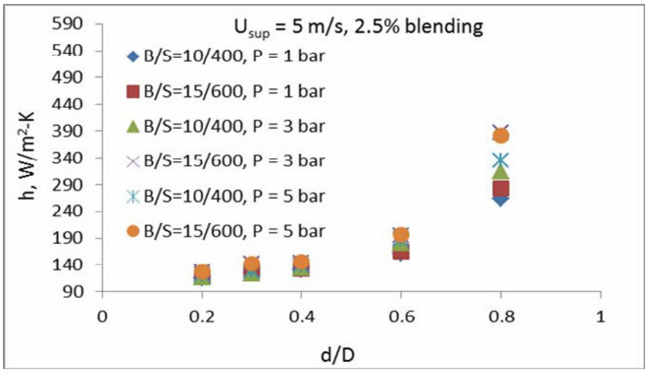


Fig.12. Comparison of radial heat transfer coefficient at 2.5 % blending

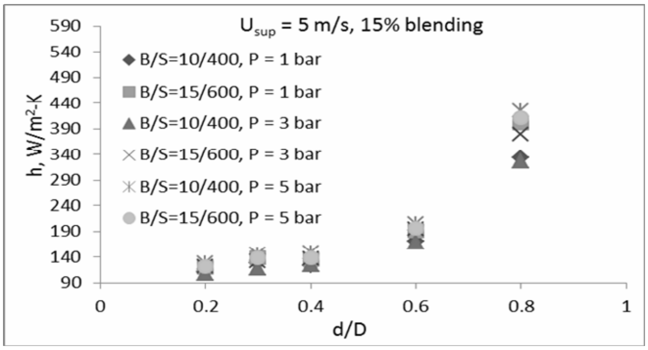


Fig.13. Comparison of radial heat transfer coefficient at 15 % blending

4. Conclusions

In the present investigation, the experiments have been conducted at four different percentage blending of biomass such as 2.5 %, 7.5 %, 15 % and 20 % in sand with two different weight composition ratios and at a superficial velocity of 5 m/s. Operating pressure is varied from 1 to 5 bar in a step of 2 bar. The summary of the experimental observations are as follows

- The suspension density increases with the increases in operating pressures.
- The axial heat transfer coefficient increases with an increase in operating pressure at all the % blending
- The radial heat transfer coefficient decreases from the wall (about 480 W/m^2-K) to the core (93 W/m^2-K) of the riser in all the operating conditions.
- The solid circulation rate increases with an increase in operating pressures, and it decreases with the increase in % blending of sawdust.
- More homogenous fluidization and uniform heat transfer coefficient has been observed with the increase in operating pressure. 7.5 - 15 % sawdust blend in sand is observed to be optimum for obtaining higher heat transfer coefficient at both the sets of weight compositions.

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