International Journal of Heat and Mass Transfer 60 (2013) 531–541

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Effect of biomass blending on hydrodynamics and heat transfer behavior in a pressurized circulating fluidized bed unit

P. Kalita [a,*], U.K. Saha [b], P. Mahanta [b]

[a] *Centre for Energy, Indian Institute of Technology Guwahati, Guwahati 781 039, Assam, India*
[b] *Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781 039, Assam, India*

ARTICLE INFO

Article history:
Received 22 May 2012
Received in revised form 9 December 2012
Accepted 13 January 2013
Available online 11 February 2013

Keywords:
Heat transfer
Circulating fluidized bed
Sawdust
Pressure
Suspension density
Solid circulation rate

ABSTRACT

The hydrodynamic and heat transfer characteristics at four different % mixing of biomass in sand (2.5%, 7.5%, 12.5% and 20%) have been investigated in a pressurized circulating fluidized bed. Experiments were performed at three superficial velocities of 6, 7 and 8 m/s. In each superficial velocity, experiments were conducted at three different system pressures of 1, 3 and 5 bar. Effects of recirculation rate have also been studied. The heat transfer characteristics have been studied at the upper splash region of the riser. Particle sizes of sand and biomass considered in the present study are 309 μm and 407 μm, respectively. From the study, it has been observed that, the heat transfer coefficient increases along the heat transfer probe and decreases with an increase in percentage blending of biomass in sand. Higher pressure and higher superficial velocity is found favorable for achieving a higher heat transfer coefficient. With increase in pressure, the heat transfer coefficient is found to be increasing with blending of biomass up to 12.5%, and then decreases as superficial velocity decreases. The heat transfer coefficient is also found to be increasing with increase in suspension density and operating pressure. Biomass blending of 12.5% in sand and a pressure of 5 bar are found to be the optimum to achieve a maximum wall to bed heat transfer coefficient and uniform circulation rate.

1. Introduction

In the recent past, more emphasis is being given to produce clean energy from biomass and other renewable sources due to rise in crude oil price and green house gas emission [1–3]. In order to utilize the available carbon neutral environmentally benign resources effectively various technologies and processes have been developed around the world [1–5]. Biomass residue such as sawdust, rice husk, bamboo dust etc. may be effectively utilized for production of liquid and gaseous fuel with the help of gasifiers and furnaces [2,3]. Besides, co-firing of biomass with coal at low percentages in the thermal power plant avoids the operating problems of biomass combustion such as ash sintering and fouling of heat exchanger surfaces [1]. Hence, biomass fuel could substitute the more expensive coal and contribute in lowering CO_2 emission. Circulating fluidized bed (CFB) technology is one of such technologies where low grade biomass fuels can be burnt in an efficient way for both combustion and gasification applications [3–6]. From the published literature, it reflects that there is a limited research in the area of heat transfer and hydrodynamics dealing with various blending of biomass in sand in a pressurized circulating fluidized bed (PCFB). Compactness, good heat transfer characteristics, fuel flexibility, and combustion efficiency makes this new PCFB technology more attractive for steam generation, gasification and combined cycle power generation [4–7]. However, as per the reported information, it is understood that more study is required for the use of this technology in future power plants with combined cycle. As reported, the design of such boiler is largely based on bed hydrodynamics and heat transfer characteristics [6].

Yates [8] 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. Yates also specifically pointed out the need for developing a mechanistic model in order to study the sintering and agglomeration in fluidized beds. Sidorenko and Rhodes [9] also reviewed the pressure effect on gas–solid fluidized bed behavior and observed that minimum fluidization velocity decreases with increasing pressure and this decrease is significant for large particles (Geldart B or D), and is generally neglected in fluidized beds of fine Geldart A powders. Many researchers have reviewed the bed hydrodynamics and heat transfer at atmospheric condition [3,7,10,11]. Gupta and Nag [6] studied the bed to wall heat transfer behavior in a 37.5 mm ID and 1940 mm height PCFB riser and observed that the heat transfer coefficient increased with an increasing operating pressure as well as with an increase in gas

---

* Corresponding author. Tel.: +91 3612583127; fax: +91 3612690762.
E-mail address: pankajk@iitg.ernet.in (P. Kalita).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.01.043

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 $kgm^{-2}s^{-1}$
h	heat transfer coefficient
ΔH	difference of height in manometric fluid measured in cm of water column
I	supply current to the hear coil
L_a	solid accumulation height in m
L_m	difference between two consecutive pressure taps
q	heat flux in W/m^2
t	time to accumulate particular height after closing ball valve in sec
T_{bi}	bed temperature in K
T_{bs}	bulk surface temperature in K
U_{sup}	superficial velocity in m/s
V	supply Voltage
ε	bed voidage
ε_{mf}	bed voidage at minimum fluidization
ρ_g	gas density in kg/m^3
ρ_s	solid density in kg/m^3
ρ_{sus}	suspension density in kg/m^3

superficial velocity. Further, with the increase in pressure, the bed voidage increased in the bottom zone of the riser and decreased in the top zone. This caused the suspension density to rise at the top zone. Similar kind of findings have recently been observed and reported by Kalita et al. [12,13]. They have studied the effect of operating pressures, solid inventory, superficial velocity and solid circulation rate on bed hydrodynamics and heat transfer in a riser of ID 50 mm and height of 2000 mm PCFB unit. Shen et al. [14] carried out test on a 6 m high and 80 mm ID tube PCFB cold test rig and suggested that with the increase in operating pressure there was a tendency of shift from aggressive fluidization to dispersion fluidization, which might have decrease solid concentration near the wall. This may result in opposite effect of pressure on the heat transfer. Reddy and Basu [15] developed a heat transfer model to predict heat transfer in a PCFB furnace. They found that with increase in pressure heat transfer coefficient was increasing as gas density and cluster thermal conductivity increases with pressure. They also observed that both the minimum fluidization velocity and the particle terminal velocity decrease with pressure. The model predictions were validated against the experimental data obtained from a PCFB riser of 52.4 mm in diameter and 2020 mm height and found similar behavior to those of Shen et al. [14], Wirth [16] and Molerus [17]. A host of researchers [18–21] developed heat transfer models independently to predict the heat transfer coefficient. Among the developed models, the model developed by Reddy and Basu [15] is found suitable for estimation of heat transfer coefficient in a pressurized CFB. Gungor and Eskin [22] developed a two dimensional model considering the hydrodynamic behavior of CFB to investigate the effect of superficial velocity on bed hydrodynamics. Richgerg et al. [23] 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 results obtained were 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. Wiman and Almstedt [24] measured hydrodynamics, local tube erosion and local instantaneous bed-to-tube heat transfer experimentally in a cold pressurized fluidized bed, with two horizontal tube banks having different tube packings. They observed that, an increased pressure causes a transition towards dispersedly bubbling, or turbulent, bed behavior and reduces the erosion significantly. Averaged heat transfer coefficient is reported to be higher for the sparse tube bank than for the dense tube bank. Hydrodynamic model with binary particle diameter to predict axial voidage profile in a CFB combustor was studied by Li et al. [25]. They observed that binary particle diameter model is proposed to better predict the axial voidage profile in the CFB boiler. Puchner et al. [26] studied the variation of bed material and operating parameter for a pressurized biomass fluidized bed process. In this study, authors concentrated the effect of parameters on the product of the gasification.

Although much work has been done on the investigation of bed voidage profile, solid circulation rate and heat transfer at varied system pressure both in bubbling and circulating fluidized bed, there is no specific information about the investigation of hydrodynamics and heat transfer at varied percentage mixing of biomass in sand. In the present investigation, an emphasis is being given to study the hydrodynamic characteristics and axial heat transfer coefficient at the upper splash region of the riser at varied system pressure and superficial velocity.

2. Material and methods

A pressurized circulating fluidized bed (PCFB) unit comprising a riser made of stainless steel, a transparent downcomer, and a cyclone separator made of mild steel was fabricated and instrumented in order to investigate the hydrodynamics and heat transfer at varied pressure condition. The schematic diagram of the experimental setup is shown in Fig. 1. The riser considered in the present study is of 54 mm ID and 2000 mm height and 3 mm thickness. The PCFB unit contains a cyclone separator having a barrel diameter of 80 mm and height of 160 mm. Entrained solids are recovered in a cyclone separator and are returned to the bottom of the riser column through a transparent return leg of 24.5 mm ID. The upper splash region of the riser is heated electrically to study the heat transfer characteristics. Air is supplied by a high pressure centrifugal blower and a compressor. The air flow rate is measured by a standard orifice meter (BS 1042) and is regulated by an air control valve and a bypass arrangement. The designed distributor plate is of straight hole orifice type having 16.8% opening area. This is fixed at the bottom of the riser column. Static pressures, and hence bed voidages, are measured along the riser height at 6 (six) different locations such as 120, 192.5, 370, 495, 970 and 1570 mm above the distributor plate. Suspension densities at those points have also been calculated. Fine wire mesh (BS 400, 200 μm) and cigarette filters are used at the pressure taping ends to minimize 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. Other techniques for measuring voidage in fluidized beds involve the use of capacitance probes, optical fibres, X-ray or γ-ray attenuation and capacitance tomographic imaging [27–29].

The heat transfer probe is located at a height of 1300 mm above the distributor plate. Internal diameter and height of the heat transfer probe are 54 mm and 500 mm, respectively (Fig. 2). Five thermocouples are facilitated to measure the surface temperature and five thermocouples are embedded to the core of the heat transfer probe to measure the bed temperature at an interval of 100 mm