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Study of bed-to-wall heat transfer with twisted tape at the upper splash region of a pressurized circulating fluidized bed unit

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ABSTRACT

In the present investigation, bed-to-wall heat transfer coefficient was studied at the upper splash region of a pressurized circulating fluidized bed (PCFB) riser of internal diameter 54 mm and height of 2000 mm. The experiments were carried out at three different temperatures. At each temperature, experiments were performed at three different operating pressures viz. 1, 3 and 5 bar to investigate the influence of operating pressure. At each pressure condition, bed temperature distributions along the height of the riser were investigated. The superficial velocity was maintained constant throughout the experiment at 7 m/s. The effect of twisted tape inserts on heat transfer at the upper splash region of the riser was studied at three different solid inventories of 400, 600 and 800 g and the results obtained are compared without twisted tape inserts. The average particle size of sand used in the experiment was of 307 μm. The overall uncertainty in calculating the heat transfer coefficient was found to be ±12.3%.

1. Introduction

Circulating fluidized bed (CFB) technology utilizes membrane wall water tubes to extract heat from the hot bed to the water flowing through the tubes [1]. As the water rises up the tubes it absorbs heat from the furnace, converting part of it into steam. The generated steam is collected in the steam drum and utilized as per requirements. The water wall tubes are generally welded by means of fins between them in the form of panels to make an airtight enclosure around the CFB furnace. If the area of the furnace wall can be increased through the use of fins projecting into the furnace, it may be possible to provide a much greater heat absorption in the furnace wall [2]. This may allow the boiler furnace to be more compact or even less tall. Ali [3] studied the bed-to-wall heat transfer in a hot CFB unit of bed cross section 102 mm × 102 mm and height of 5.25 m and also investigated the effects of rectangular fins and pin shapes on heat transfer under different operating conditions. He had used LPG for heating the CFB unit. Ali [3] also developed a theoretical model to predict the heat transfer coefficient under the similar operating conditions and compared the results. As reviewed by Basu and Nag [2], the heat transfer from bed to wall has been investigated by a number of researchers [4–9]. Most of the researches were conducted experiment on conventional membrane tubes, and few studies were found to enhance the heat transfer coefficient by using membrane tubes with longitudinal fins on the tube crest [4,5,9]. Chinsuwan and Dutta [10] studied heat transfer for the membrane tube with two longitudinal fins and the comparison of heat transfer behaviors between longitudinal finned tubes and membrane tubes in a cold model riser of cross-section 100 mm × 100 mm and height 4.8 m. They compared the performance of different configuration at a superficial velocity of 8 m/s at a bed temperature of 75 °C. The use of passive heat transfer mechanism to enhance the heat transfer at the upper splash region of the CFB riser was not found in the open literature.

The heat-transfer coefficient in a CFB riser is influenced by a number of factors, including air flow, solid circulation rate, solid inventory, and particle size distribution [1,2,11–13]. Much of the effect of these parameters on the heat transfer is due to their influence on the suspension density [1]. The heat transfer coefficient is found to vary as square root of the cross-section average suspension density [14]. Divilio and Boyd [15] 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 noticed 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 [13] studied the bed to wall heat transfer behavior in a 37.5 mm ID and 1940 mm height PCFB riser where the heat

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Nomenclature

A_{ts}	tube surface area (m^2)	T_b	bulk bed temperature (°C)
C_p	specific heat (kJ/kg °C)	T_{ts}	tube surface temperature (°C)
h	heat transfer coefficient	$T_{w,in}$	water inlet temperature (°C)
$\dot{m}_w$	mass flow rate of water (kg/s)	$T_{w,out}$	water outlet temperature (°C)
Q	rate of heat transfer from the bed to the water (W)		

transfer coefficient was found increasing with an increase in operating pressure as well as 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. Kalita et al. [16] have also investigated the similar behavior.

Moreover, the hydrodynamics of gas–solid interactions at different operating conditions plays a key role in investigating the heat transfer characteristics in the CFB loop. The hydrodynamic characteristics along the height of the riser and the heat transfer characteristics at the upper splash region of the riser have been investigated at different operating conditions in 54 mm ID riser and height of 2000 mm [16,17]. They have found that, with the increase in operating pressure and superficial velocity, the heat transfer coefficient increases from the bottom to the top of the heat transfer probe due to accumulation of more solids at the upper splash region. This is the result of increase in drag force on the solid particles as the pressure increases which lifted up the solids to the top of the riser.

The use of twisted tape to enhance the heat transfer coefficient in CFB is found to be limited even though large number of research publications is available for enhancement of heat transfer with the help of fins. In view of the above, in the present investigation, the heat transfer coefficient is investigated and compared without and with twisted tape inserts. The effect of solid inventory, and operating pressures was also investigated in order to compare the heat transfer at the upper splash region of the riser.

2. Material and methods

The schematic diagram of a hot pressurized circulating fluidized bed (PCFB) setup is shown in Fig. 1. The unit comprises of a riser, a downcomer, a cyclone separator and a dust filter. The riser is made of stainless steel of ID 54 mm, height of 2000 mm and thickness of 3 mm. The riser comprises of six sections (starting from the lower splash region of the riser) of height 600, 200, 400, 200, 400 and 200 mm. These sections are connected by joining one above the other with the help of flanges. A metallic gasket of thickness 3 mm placed in between the flange in order to minimize hot gas leakage. Four sets of nuts and bolts are used to join two sections. A kanthal heater coil of capacity 3500 W (resistance of 14 Ohms) is installed at the lower section of the riser. This is wrapped over a ceramic tube of OD 24.5 mm. A required voltage and hence, current is supplied to the heating element through auto-transformer–ammeter–thermocouple-controller assembly to attain a predefined temperature. Adequate electrical and thermal insulation are provided. For thermal insulation, ceramic wool and ceramic rope are used throughout the riser. The axial heat loss by conduction is also prevented by providing insulating gasket in between the flanges in the joints. The PCFB unit contains a mild steel cyclone separator of barrel diameter 80 mm and height 160 mm. The entrained solids are recovered in a cyclone separator and are then transported to the bottom of the riser column through a return leg of ID 24.5 mm. Air is supplied to the CFB unit through the bottom of the riser by a high pressure centrifugal blower (Model No.: 710, motor capacity: 20 HP) and a compressor (Make: Ingersoll Rand (IR), Model No.: S-01480). 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. Air flow rate is also observed with the help of a rotameter installed just before entry of air to the CFB unit. 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. Both surface and bed temperatures are measured by using chromel–alumel thermocouples. Surface temperature is also measured by using a non contact type infrared thermometer. These thermocouples are connected to an Agilent 34972 LXI data acquisition/switch unit for the display of temperature reading. Finally, the measured data is recorded in a computer for further analysis. 4 (four) dial gauges are used to investigate the drop in pressure along the height of the CFB riser. Fine metallic wire mesh of size 200 μm is used at the pressure taping ends to minimize the pressure fluctuations. Heat transfer coefficients were investigated and compared the performance without and with installation of twisted tape inserts at the upper splash region of the riser. The temperature profiles along the riser height were also recorded with the variation of solid inventory.

Two heat transfer probes of height 400 mm were fabricated and installed at the upper splash region of the riser at a height of 1400 mm above the distributor plate. The internal diameter of all the probes is same as the diameter of the riser i.e. 54 mm. The configurations of the two probes are shown in the Figs. 2 and 3. Probe-1 (Fig. 2) facilitates with three copper tubes without twisted tapes and the probe-2 (Fig. 3) is facilitating with three copper tubes with twisted tapes of twist ratio 4 in between the tubes. The outer diameter and length of the copper tube are 10 and 300 mm, respectively. The tubes are welded on a copper strip which connects all the tubes to hold the tube assembly. A predefined flow rate of water (200 ml/min) was allowed to pass through the middle tube installed in between the twisted tape. The static constant head is maintained at the water reservoir through which water is flowing. The inlet and outlet temperature of the water flowing through the copper tube was measured by using two independent thermometers to calculate the heat flow. In each probe adequate provisions are made for measurement of bed and surface temperatures with the help of thermocouples. Finally, the heat transfer coefficient is calculated by using the value of heat flow and surface area of the tube. Ceramic wool and ceramic rope is used around the probe for thermal insulation. 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 chromel–alumel thermocouples which are connected to Agilent 34972 LXI data acquisition/switch unit for display. Local sand having mean particle diameters (dp) of 307 μm, and density of 2300 kg/m^3 was used as the bed material in the study.

3. Experimental

At the beginning of the experiment, blower is turn on to circulate air around the CFB loop. The temperature of the air passing through the CFB loop is recorded before the heater turn on. After 15 min of continuous running of air through the loop i.e. after