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# RADIAL HEAT TRANSFER INVESTIGATIONS IN A CIRCULATING FLUIDIZED BED BURNING MAKARWAL COAL

*W. A. Khan[1]*, K. Shahzad[2], M. Saleem[2], N. A. Akhtar[3] and S. Tahir[1]*

[1]NFC Institute of Engineering and Fertilizer Research, Faisalabad, Pakistan,

[2]Institute of Chemical Engineering and Technology, University of the Punjab, Lahore, Pakistan

[3]National Textile University, Faisalabad, Pakistan.

## Abstract

In the present paper, a detailed parametric study is conducted on the radial heat transfer studies in a locally fabricated circulating fluidized bed combustor by burning Makarwal coal. The variations of radial heat transfer coefficients in a CFB combustor with different operating parameters are investigated. The experimental set up consists of a riser of a circulating fluidized bed (152 mm ID and 6 m high). A radial heat transfer probe (2" thick & 15.4 cm ID) was used for these investigations. Silica sand of 2500 $Kg/m^3$ and having average particle size of 125 µm is used as bed material. A detail radial temperature profile was also investigated during the experimental runs. It was found that radial heat transfer coefficient increased with increase in suspension density, bed temperature and solid circulation rate.

**Keywords:** Coal, Combustion, Circulating fluidized bed.

*Corresponding Author e-mail: engrwaqarali@gmail.com
Phone no. 03334333494

## 1. Introduction

Circulating fluidized bed is one of the promising fluidized bed technologies which are used these days for the combustion of conventional fuels like coal and biomass. Circulating fluidized bed combustors are widely used for generation of energy and steam due to its higher combustion efficiency and comparatively better gaseous emissions control. The intense lateral mixing of solids and gas in circulating fluidized beds yields rapid generation of heat and dispersion to the riser walls. Many investigators studied heat transfer in CFB. The first ever study on heat transfer in fluidized bed was carried out by Mickley [18]. Many comprehensive reviews on heat transfer have been also presented [6, 11, 12, 15]. Fluid dynamic model was also employed to simulate bed-to-wall heat transfer in CFB [14]. The bed-to-wall heat transfer coefficient is roughly proportional to the square root of the mean suspension density [11]. Heat transfer mechanisms in a CFB are complex. Advantages of CFB includes favorable rate of heat transfer to or from the wall. Many CFBC contain heat transfer surfaces to control the temperature. The arrangement of heat transfer surface, however, is critical in design, operation and efficient control of a CFB. Correct estimation of heat transfer coefficient is the key to success in controlling the CFB operation. However, the dependence of heat transfer behavior on the operating parameters such as suspension density, temperature, superficial gas velocity, and heat transfer surface area makes the generalization of heat transfer coefficient difficult and its understanding is complicated.

Therefore the objective of the present study is to investigate, in detail the effect of different operating parameters on radial heat transfer coefficient in a locally fabricated circulating fluidized bed combustor.

## 2. Experimental

The CFB system employed in this study (Fig.1) was comprised of a riser of diameter 152 mm and height of 6 m, primary and secondary cyclones, an external heat exchanger (EHE) and an L-valve, for controlling the circulation rate of solids. The whole system was made of stainless steel and was insulated with ceramic fiber on its outer surface. Primary air was supplied to the base of the riser through an air distributor, while the secondary air was injected through injector nozzle located 94.4 cm above the primary air distributor. Silica sand, having sauter mean diameter (SMD) of 125 μm and a particle density of 2500 $kg/m^3$, was used as the main circulating bed material.

The total inventory of the bed material was 50 kg. Makarwal coal was used in these investigations. Proximate and ultimate analysis of coal is shown in Table 1. Coal particles were crushed to less than 1 mm size and typically their SMD was about 0.48 mm.

The bed was initially heated by a natural gas burner to a temperature of around 500 °C (depending on the type of coal), before coal was pneumatically fed to the combustion chamber. The natural gas burner was switched off when the coal started burning in the combustion chamber. Experimental results were recorded under steady state conditions. Limestone ($CaCO_3$) containing 98.8% calcium carbonate was also added as the sulfur capture sorbent. Limestone particles with a SMD of 129 μm and particle density of 2730 $kg/m^3$ were fed by a screw feeder and pneumatically transported into the riser. Two

different positions for limestone addition were adopted, one through a separate limestone injection port, which was 194 cm above the primary air distributor. Solids entrained by combustion gases from the riser were collected by the primary cyclone and fed to the EHE. The solids were returned to the riser at a controlled rate through the L-valve.
Combustion gas temperatures along the riser were controlled by the coal feed rate and through the solids circulation rate. Temperatures along the riser height were measured by (CA-type) thermocouples. Differential gas pressure between the bottom (94.4 cm above the primary air distributor) and top (550 cm above the primary air distributor) of the riser was closely monitored by U-tube manometers and used as the indication of circulation stability. All reported experiments were carried out with a fixed bottom to top pressure differential of 60mm $H_2O$. The concentration of the Oxygen in flue gas was measured by Para-magnetic gas analyzer.

For the heat transfer studies along the radial direction, a cooling plate (circular ring) having the same material as of CFB i.e. SS-304 was designed and fabricated. Fig. 2 shows the schematic of the cooling plate. The plate has dimensions of 2" thickness and15.4 cm ID. A cooling water jacket having 1.8 cm thickness and depth of 4 cm was designed and water was circulated through the cooling plate by a motor driven pump. Water flows inside the jacket. The inlet and outlet temperature of water was measured by installing temperature gauges.

Water flow rate across the jacket was measured by inserting rotameter of capacity of 100-1000 ltr/hr (Model KEDE- F702).Temperature at the inlet and outlet of the jacket gave the temperature difference across the jacket. Heat absorbed by water was measured and thus heat transfer coefficients across the bed were calculated. A space for four thermocouples (K-type) was provided on the plate which measured the temperature distribution along radial direction. These thermocouples were inserted at specified distances i.e. at the wall, 3 cm, 5 cm and 7.4 cm on the plate to see the temperature profile. This cooling plate was inserted at ‘3ft’, 6 inch above the distributor plate. The schematic of cooling plate is given in figure 2. The temperature of each thermocouple was red out on respective digital temperature indicator on the main panel .This temperature difference was used to calculate the “Heat Transfer Coefficient” throughout the experiments. An air supply system with a new air blower was used for the supply of air to CFBC. Primary as well as secondary air was measured by installing rotameter & orifice meter.

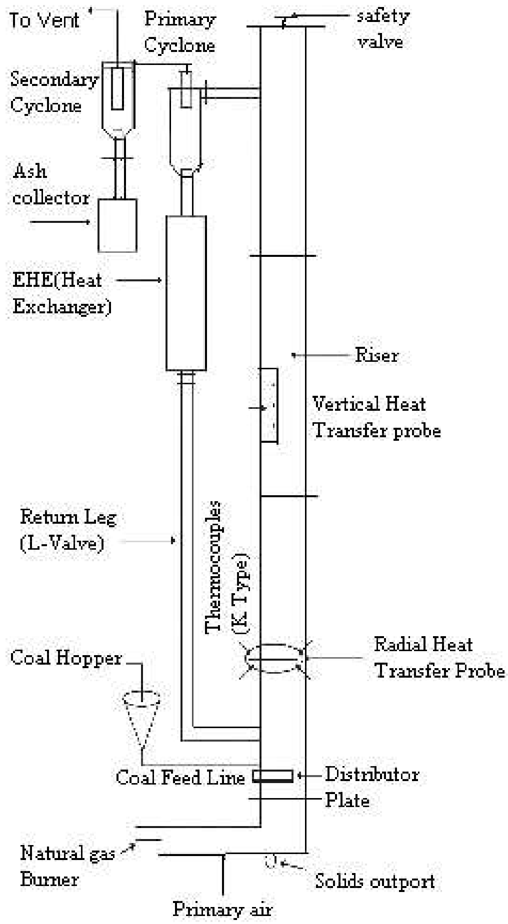



**Figure 1:** Schematic of CFBC at Punjab University

| Proximate Analysis [%] | |
|---|---|
| Parameter | Makarwal coal |
| Moisture | 0.50 |
| Fixed Carbon | 38.23 |
| Volatile Matter | 46.62 |
| Ash | 14.65 |
| Ultimate Analysis [%] | |
| Carbon | 71.16 |
| Hydrogen | 5.97 |
| Nitrogen | 1.56 |
| Sulfur | 1.18 |
| Oxygen | 20.13 |
| Heating value [MJ/kg] | 26.01 |

**Table 1:** Analysis of the fuel used

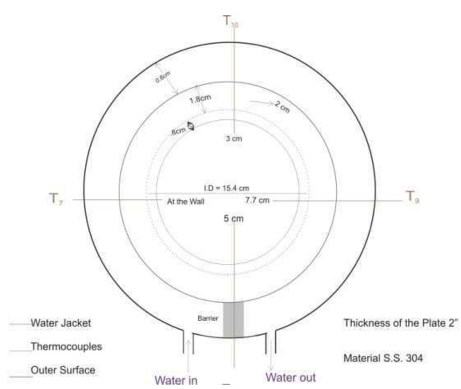
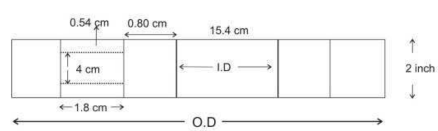



**Figure 2:** (a) Schematic of cooling plate for radial heat transfer studies [with thermocouples and accessories]




(b) Front view of Cooling Plate

## 3. Results and discussions

The effects of different operating parameters on heat transfer coefficient in the CFB combustor were investigated and are being reported. Firstly, general characteristics of a CFB combustor in term of hydrodynamic are discussed followed by axial temperature distribution and radial temperature profile. Then, effect of different operating parameters on radial heat transfer coefficient is discussed .The operating parameters which were investigated during the studies were suspension density, bed temperature, superficial gas velocity, bed temperature, particle size and solid circulation rate. The modified CFB combustor was operated under staged condition, bed temperature in the range of 500-700$^0$C and gas velocity 4-6 m/s with solid circulation rate of 20-25 kg/m$^2$ sec.

### 3.1 Temperature distribution

Heat transfer in circulating fluidized bed is directly related to the hydrodynamics of CFBC. Many researchers tried to describe this temperature distribution in CFB's. One group of researchers [22, 3, 20] found a core-annulus structure in the riser while the others related this temperature distribution to the thermal boundary layer [16]. The following results report in detail the axial and radial temperature distribution in the CFBC with the suspension density.

#### 3.1.1. Variation of temperature with suspension density

Figures 3-4 show typical temperature distribution between the bottom and the top region of the riser with suspension density. From the results, it is clear that the difference in temperature between bottom and the top of the riser decreased with suspension density. The results exhibits that the axial distribution in the riser is more uniform at greater values of suspension density. This is because of the fact that uniform distribution of circulating solids brings uniformity in temperature distribution in the riser of CFB.

The reported variation in temperature difference between the bottom and the top of the riser gives the efficient operation of CFB combustor. A proper suspension density is necessary for maintaining a uniform axial temperature distribution in the riser. It was felt that in order to run the CFBC with a temperature difference of less than 50°C between the bottom and the top of the riser, the suspension density should be at least 10 Kg/m$^3$. This uniform axial temperature distribution improves the stability of CFBC operation.

The variation of the suspension temperature at the bottom and top of the riser with suspension density can be interpreted by the heat transfer between gas and particles. Continuous heat transfer from gas to particle takes place as these particles move from the bottom to the top of the riser. This process of heat transfer combined with heat losses through the riser wall causes a temperature drop from bottom to the top region.

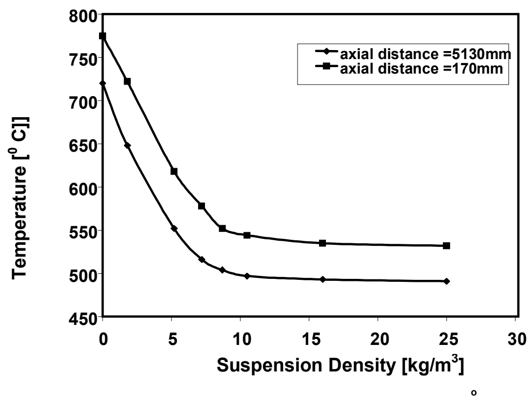



**Fig 3:** Variation of temperature between bottom and top of the riser with suspension density [U=5 m/s, Tb =750$^0$C]

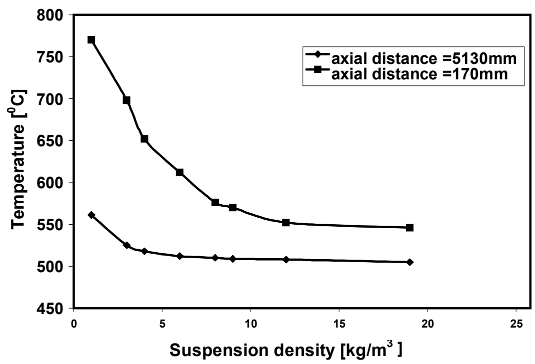



**Fig 4:** Variation of temperature between bottom and top of the riser with suspension density [U =4.5 m/s, Tb =600$^0$C]

### 3.1.2. Typical radial temperature profile

The effect of suspension density on radial temperature profile at different bed temperatures and superficial gas velocities in the riser is shown in the Fig 5-8 respectively. These result show that he temperature increases as the distance increases from the wall in the beginning [up to 50mm distance] and then becomes uniform. The same behavior was also observed over wide range of suspension density and temperature. It is obvious from the experimental results that maximum temperature gradient exists between the thermocouples located at 30 mm and 50 mm distance from the riser wall and it usually decreases with increasing suspension density. A small difference in pressure clearly shows a uniform bed temperature distribution in the riser. Hence, from all these reported results it is noticed that the temperature becomes more uniform with increasing suspension densities. These results are quite similar with the results of previous researchers [17].

This radial temperature distribution in CFB combustor suggests that the riser flow is typical of the upward solid motion in the core of the riser and downward motion along the walls of CFBC which is characterized as core annulus [C/A] flow structure. This kind of flow structure has also been reported by many other researchers [17, 6].

At bed temperature i.e. 680, 720,775, and 820°C, it is clear that the shape of the radial profiles becomes flatter with increasing suspension density but becomes uniform again for higher values of suspension density. These results are in agreement with the work carried by [17].

### 3.2. Radial heat transfer studies

A series of experiments were performed by using Makarwal coal in the CFBC. Results were taken for radial heat transfer studies.

#### 3.2.1. Effect of suspension density on heat transfer coefficient

Suspension density is found to be the most dominant parameter influencing the heat transfer mechanism in CFBC [5, 8, 11, 12]. All these investigators found a direct relationship between these two variables.

An attempt was also made to see this effect during combustion of coal in CFB and results are reported in Figure 9. These results were obtained for the bed temperature in the range of 600-750°C and superficial gas velocity was varied between 4.5-5.2m/s.

From these results, it is confirmed that suspension density has a direct relation with heat transfer coefficient. Transient heat conduction through the particles being the major mode of heat transfer in CFBC, and therefore it causes an increase in the heat transfer coefficient with the increasing suspension density [5]. Higher value of suspension density indicated more particles per unit volume and hence resulted in higher particle convective heat transfer contribution in the total heat transfer. The obtained results were in agreement with the findings of other researchers [11, 17, 13, 2]

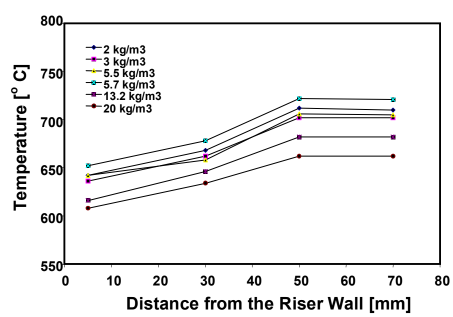



**Fig. 5:** Radial Temperature Profile in the Riser [Tb = 720 $^{0}$C, U=5.0 m/s]

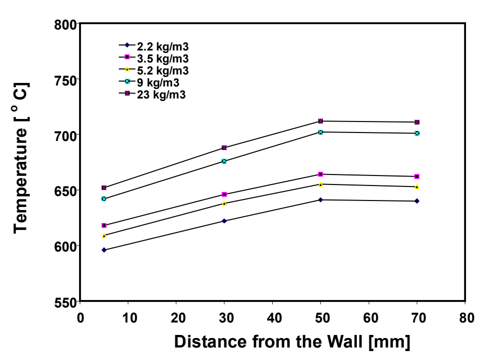



**Fig. 6:** Radial Temperature Profile in the Riser [Tb =775 $^{0}$C, U = 5 m/s]

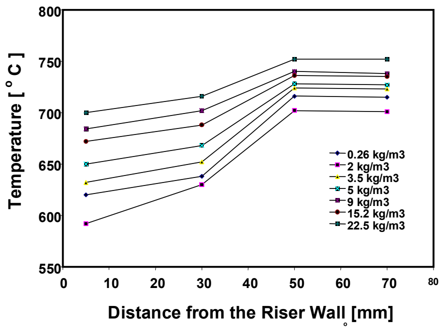



**Fig. 7:** Radial temperature profile in the riser [Tb =800 $^0$C, U = 5.6 m/s]

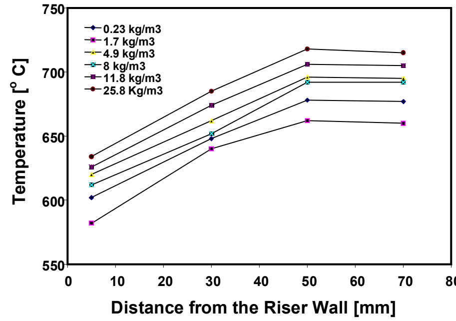



**Fig. 8:** Radial temperature profile in the riser [Tb = 820 $^0$C, U = 5.8 m/s]

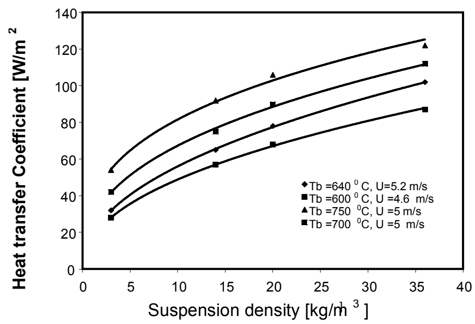



**Fig 9:** Effect of suspension density on heat transfer coefficient

### 3.2.2 Effect of superficial gas velocity on heat transfer coefficient

'Bed-to', wall heat transfer coefficient versus suspension density was reported at two superficial velocities [4.9 m/s and 5.3 m/s].Although "h" varied with suspension density over the reported range, however, "h" was slightly lower at high velocity at all suspension densities. The similar trends were also reported [9, 17a-b, 19, 16]. The results are provided in figures (10, 11).

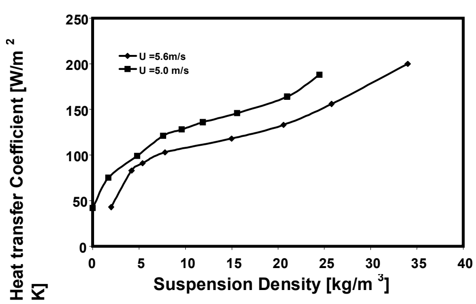



**Fig.10:** Effect of Superficial gas Velocity on heat transfer coefficient [Tb = 700 $^0$C]

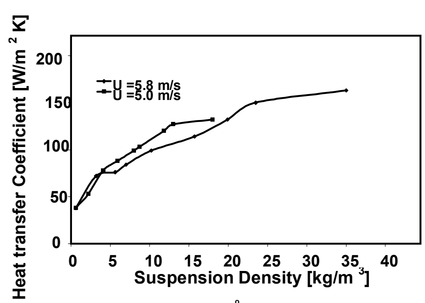



**Fig.11:** Effect of Suspension density on heat transfer coefficient [Tb =750 $^0$C]

### 3.2.3 Effect of bed temperature on heat transfer coefficient

Experiments were conducted in the modified CFBC for different bed temperatures in the range of 500-800°C to see the variation of the heat transfer coefficient with bed temperatures at different values of suspension densities (Fig.12). The result indicates that the heat transfer coefficient increase by increasing the bed temperature in all cases. It is due to the fact that this increase in temperature can reduce contact resistance as well as cluster thermal resistance. It can also be attributed, because of increase in thermal conductivity of the fluidizing gas and increased radiation contribution of the suspension at higher temperatures. The results are similar to those as described by other as well [17, 21, 13].

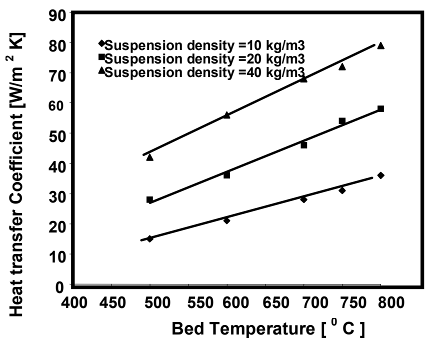



**Fig.12:** Effect of bed temperature on heat transfer coefficient

### 3.2.4 Effect of particles size on heat transfer coefficient

Experiments were conducted to investigate the effect of different coal particle size on heat transfer coefficient in the CFB. The previous studies [5, 8, 13] pointed out this parameter as critical in heat transfer studies in the CFB combustor. The obtained results are reflected in figure 13.

The results show that smaller particles size yield higher heat transfer coefficient and vise versa. Finer particles have a low thermal resistance than larger ones and therefore show a higher heat transfer coefficient [10]. The results obtained through this study are similar with the work of previous researchers.

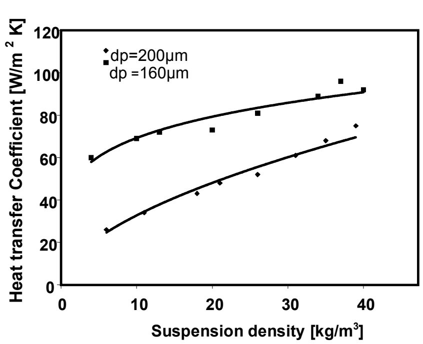



**Fig.13:** Effect of suspension density on heat transfer coefficient

### 3.2.5 Effect of solid circulation rate on heat transfer coefficient

Solid circulation rate is another key parameter in the studies of heat transfer in CFBC [9,10,15,27]. This effect is also useful in the calculations of wall- to- bed heat transfer coefficient. Therefore, attention was also given to see the effect of solid circulation rate on heat transfer coefficient in the present study. The result obtained is reported in the Fig. 14.

The result indicates an increase in heat transfer coefficient with increasing the solid circulation rate. It is due to the fact that the solids injected in the column increase the suspension density and thereby increasing heat transfer coefficient with increasing solid circulation rate in the bed. The figure 14 again reveals suspension density as the most significant parameter in the designing of CFB.

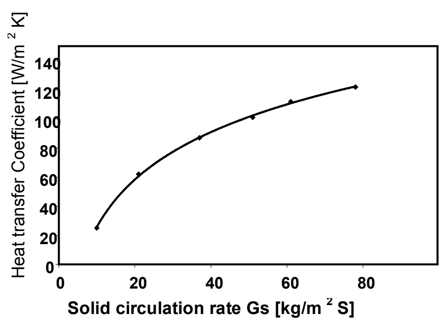



**Fig.14:** Effect of solid circulation rate on heat transfer coefficient [Tb =750 $^0$C, U =5 m/s]

## 4. Conclusion

Effects of different operating parameters on radial heat transfer coefficient were the main focus of this study. As heat transfer coefficient is directly related to the performance of the heat exchangers. From the experimental work conducted, the following conclusions can be drawn:

- Suspension density was found as the most significant factor in the heat transfer studies and it affected radial and axial temperature distribution in a CFB combustor.
- Radial heat transfer coefficient increased with increasing suspension density and bed temperature.
- Effect of superficial gas velocity was found not very significant in radial heat transfer studies.
- Radial heat transfer coefficient was found to increase with solid circulation rate also.
- Smaller particles size yield higher heat transfer coefficient and vice versa.

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