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HEAT TRANSFER IN A HIGH TEMPERATURE FLUIDIZED BED

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Abstract–The heat transfer characteristics between the bed and immersed tube in a high temperature fluidized bed (7.5 cm I.D.×70 cm H) were investigated with sand and iron ore particles. The heat transfer coefficients were measured at operating temperatures of 200-600°C and gas velocities of 1-10 U_{mf}. The bed emissivity measured by the radiation probe was found to be 0.8-0.9. The experimentally obtained radiative heat transfer coefficient was in the range of 30-80 W/m^{2}K for the operating temperature of 400-800°C and the contribution of radiation to total heat transfer was about 13% and 18% for the operating temperatures of 400°C and 600°C, respectively.

Key words : Fluidized Bed, Radiative Heat Transfer, Bed Emissivity

INTRODUCTION

Industrial applications of fluidized beds are primarily in the chemical, petroleum, and metallurgical industries. One of the remarkable features of the fluidized bed is its temperature uniformity. It is required for catalytic reactors to maintain a given temperature level in the bed by removing (or adding) a definite amount of heat by contact with an appropriate heat exchange surface. Consequently, a bed-to-immersed tube heat transfer coefficient is needed to design heat exchanger tubes. Experimental data of the total heat transfer coefficient between the fluidized bed and heat transfer tubes have been reported in the literature [Bak et al., 1985; Choi et al., 1985; Cho et al., 1996]. Some overall heat transfer measurements obtained at high temperatures are rather limited. With radiation probes, Ozkaynak et al. [1983], Mathur and Saxena [1987], and Han [1992] directly measured the radiative heat transfer coefficient between hot beds of coarse particles and small vertical surfaces immersed in the bed and found that the radiation contribution to heat transfer increased from 10% to 30% with a temperature increase from 400°C to 800°C.

In this study, the effect of operating variables on the heat transfer coefficients in the medium temperature ranges such as 400-600°C was investigated for the temperature control of fluidized bed catalytic reaction such as regeneration of spent catalyst with oxygen. Also the contribution of radiation to total heat transfer in the medium temperature ranges was also investigated.

EXPERIMENTAL

A schematic diagram of the experimental test set-up is shown in Fig. 1. A cylindrical bed had a diameter of 7.5 cm and height of 70 cm and was made of stainless steel. The gas distributor was a perforated plate. The heat transfer tube immersed in the bed was made of stainless steel and had a diameter of 0.625 cm. Water was employed as the heat transfer fluid and bed materials used in this experiment were 0.28 mm sand and

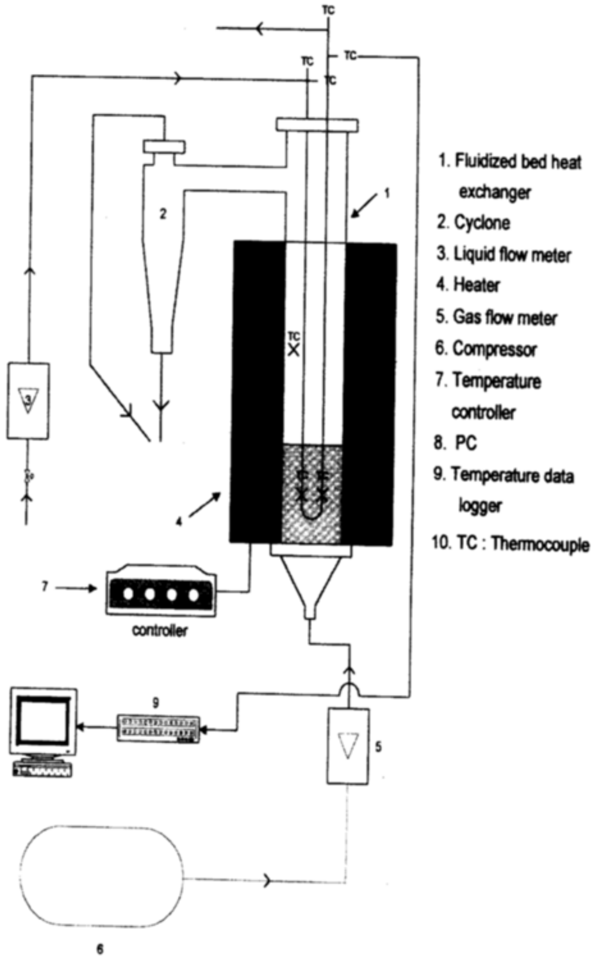

Fig. 1. Schematic diagram of experimental test facility.

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Table 1. Physical properties of particles employed

	Sand particle	Iron ore
Diameter (mm)	0.28	0.177
Density (kg/m^3)	2,500	3,850
Minimum fluidization velocity (cm/sec)	10.0	4.0

0.177 mm iron ore. The physical properties of employed particles are given in Table 1. Two K-type thermocouples were installed at the inlet and outlet of the heat transfer tube and two K-type thermocouples were located in the heat transfer tube for the measurement of bed to tube heat transfer as shown in Fig. 1. The location of the thermocouples in the heat transfer tube was 2-3 cm below the particle level of the fixed bed so that the heat transfer coefficient between bed and immersed tube was obtained during fluidization. The bed was surrounded by the 3 KW radiant heater and insulated with ceramic insulating materials. Three K-type thermocouples were inserted in the bed at different axial locations and the averaged value was taken as the bed temperature. The bed temperature was controlled by the PID controller. As the steady state of fluidization was attained at a given operating condition, the temperatures of bed and water in the tube which was immersed in the fluidized particles were recorded in the computer by the data logger for the determination of bed to immersed tube heat transfer coefficient.

In order to determine the radiation effect on the heat transfer in a fluidized bed, we used a radiative heat flux meter; details of the radiation probe are shown in Fig. 2. With that radiation probe, we could directly measure the radiative heat flux from the bed to the probe sensor area. The radiation probe consisted of a brass body, calcium fluoride window and a heat flux transducer. The radiation probe has a 1.27 cm diameter sensor area which is water cooled. The CaF$_2$ window, which is a radiatively transparent material located in front of the sensing surface, transmits the radiative heat flux from the heat source to the sensing surface. The transmittance band for CaF$_2$ window is about 0.1 to 8 micron and transmissivity was 0.9 for that wavelength range. The heat flux transducer functions according to the theory and principle of a simple thermopile. An instrument operating on these principles provides a direct readout in millivolts proportional to incident heat flux. The heat flux transducer consisted of an insulating wafer, with a series of thermocouples consisting of a thermoelement combination with consecutive thermoelectric junctions on opposite sides of the wafer. This assembly was bonded to a heat sink to ensure heat flow through the sensor. Heat received on the sensing surface of the wafer was conducted through to the heat sink. A temperature drop across the wafer was thus developed and measured directly by each junction combination embedded along the wafer. The temperature drop across the wafer, and thus the output signal, was directly proportional to the heat flux.

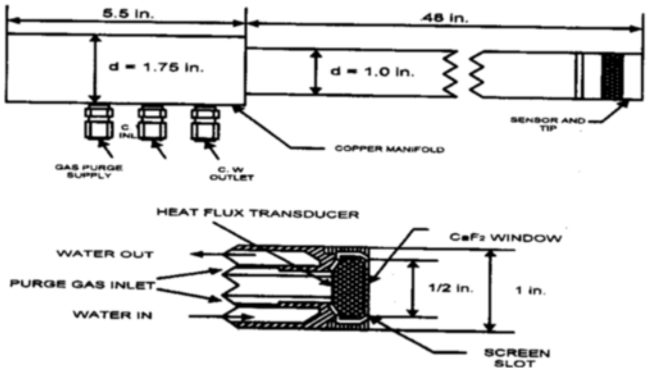

Fig. 2. Details of radiation probe.

RESULTS AND DISCUSSION

1. Effect of Temperature and Gas Velocity

The bed to immersed tube heat transfer coefficient h_o was calculated from the overall heat transfer coefficient U_o and water side heat transfer coefficient h_i.

$$U_o = \frac{\left(\frac{Q}{A}\right)}{\mathrm{LMTD}} \tag{1}$$

$$\frac{1}{U_o} = \frac{1}{\frac{1}{h_o} + \frac{1}{h_i}} \tag{2}$$

where LMTD is defined as

$$\mathrm{LMTD} = \frac{(T_b - T_i) - (T_b - T_o)}{\ln\left(\frac{T_b - T_i}{T_b - T_o}\right)}$$

and T_b, T_i, T_o represent bed temperature, inlet temperature of tube and outlet temperature of tube. The conduction resistance through the tube wall was ignored and the water-side heat transfer coefficient h_i was calculated from the correlation of Sieder and Tate [1936].

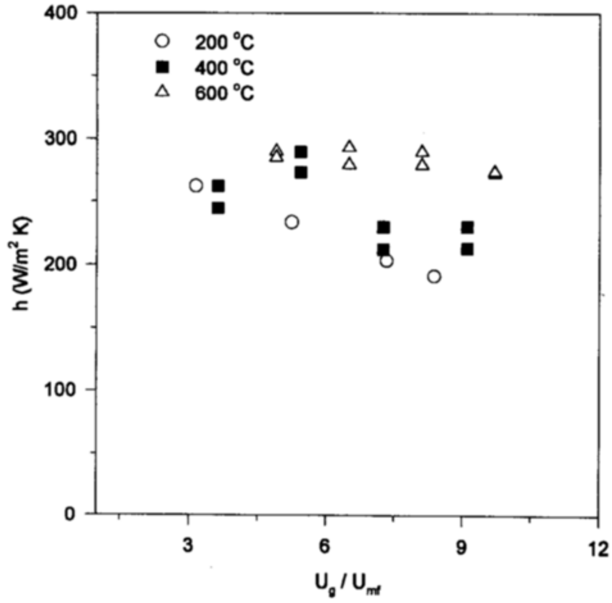

Fig. 3. Effect of temperature and gas velocity on heat transfer coefficient for sand particle.

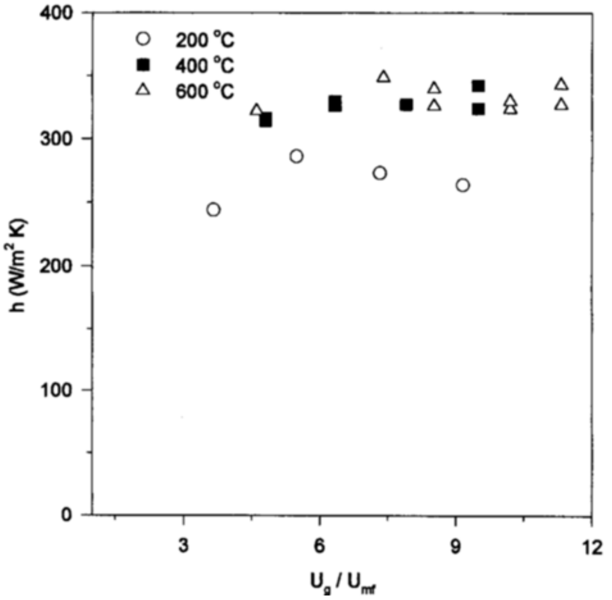

Fig. 4. Effect of temperature and gas velocity on heat transfer coefficient for iron ore particle.

$$Nu=0.027\ Re^{0.8}\ Pr^{0.33} \tag{3}$$

The obtained bed to tube heat transfer coefficients (h_o) with different gas velocity and bed temperature are shown in Fig. 3 and Fig. 4 for sand and iron ore particles, respectively. For the operating temperature ranges the heat transfer coefficients were 200-300 W/m²K for sand particles and 250-350 W/m²K for iron ore particles, respectively. The higher heat transfer coefficient of iron ore particles may come from the smaller particle size and larger thermal conductivity than the sand particles. It was also found that the heat transfer coefficient decreased slightly as the gas velocity increased for sand particles as shown in Fig. 3. This can be explained using the packet model. Increasing the fluidizing velocity also increases the number of bubbles. Therefore the conductive-convective component of emulsion phase decreases with increasing fluidizing velocity. From Fig. 3 and Fig. 4, we can also see the temperature effect on the heat transfer coefficient. A detailed analysis of the temperature effect is given in the next section.

2. Bed Emissivity

In a heat transfer study of fluidized beds the bed emissivity is a very important radiative property particularly in the high temperature fluidized bed. For the measurement of bed emissivity, the radiation probe was inserted vertically into the bed surface and the radiative heat exchange between bed and sensor surface was measured. Since the radiative heat flux was measured, we could calculate bed emissivity by applying the Stefan-Boltzmann equation as follows;

$$\frac{Q_r}{A}=\frac{\sigma(T_b^4-T_w^4)}{\frac{1}{\varepsilon_b}+\frac{1}{\varepsilon_w}-1} \tag{4}$$

since we know the radiative heat flux and emissivity of the sensor surface (ε_w=0.98), the bed emissivity was determined. Another method of determining the bed emissivity was employed in this study. Since we also measured the heat transfer coefficient at room temperature, the radiative heat flux was calculated from the value of heat flux at the high temperature experiment minus the heat flux at the room temperature experiment with the assumption that radiative heat flux was negligible at the room temperature experiment. Fig. 5 shows the bed emissivity obtained from the radiation probe and the calculated value by differencing the heat flux between the high temperature and the room temperature experiment. As shown in the Fig. 5, the bed emissivity obtained in two different methods was found to be in the range of 0.8 to 0.9, and there was no significant difference in determining the bed emissivity through two different methods. It was also found that the emissivity of the bed decreased slightly with bed temperature. Baskakov [1985] presented results from experiments made with a radiation probe and found that the emissivity of the bed was in the range of 0.6-0.92 and was dependent on the particle emissivity. Ozkaynak et al. [1983] obtained bed emissivity of 0.7 to 0.8 for the sand particles of 0.73 mm and 1.03 mm at the operating temperature of 400-800°C with radiation probe. Therefore it can be concluded that the bed emissivity is higher than the gas emissivity in the gas-fired combustor where gas emissivity is generally less than 0.1 and this higher bed emissivity enhanced the radiative heat transfer from heat source to cold surfaces.

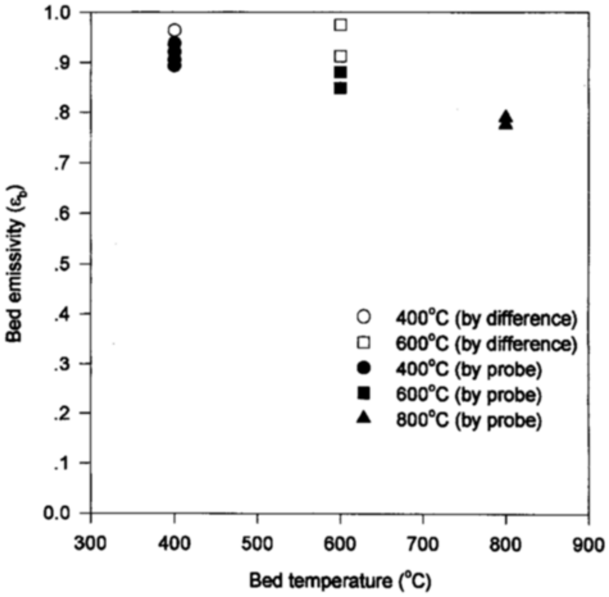

Fig. 5. Bed emissivity as a function of bed temperature for sand particles.

3. Radiative Heat Transfer Coefficient

Since the radiative heat flux from bed to radiation probe was measured, the radiative heat transfer coefficients for 0.28 mm sand particles were calculated by

$$h_r=\frac{Q_r}{T_b-T_w} \tag{5}$$

They are shown in Fig. 6 as a function of bed temperature for gas velocities of 2.0-4.0 U_{mf} condition. As can be seen in Fig. 6, the radiative heat transfer coefficient was independent on the gas velocity and increased with bed temperature. When the

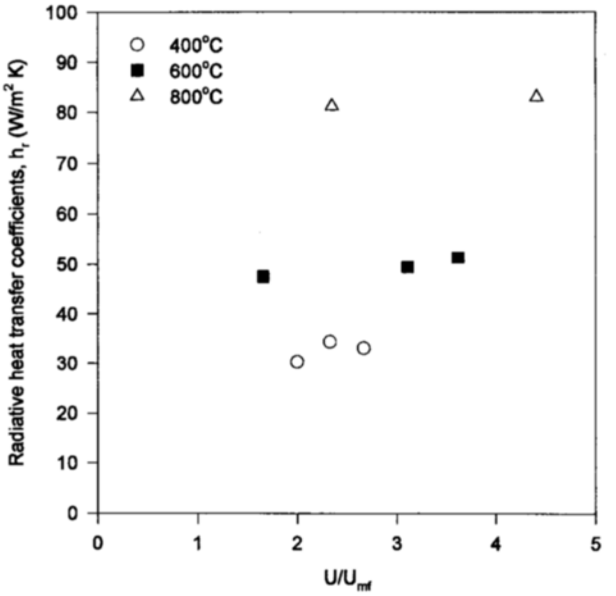

Fig. 6. Radiative heat transfer coefficient as a function of gas velocity at different bed temperatures for sand particles.

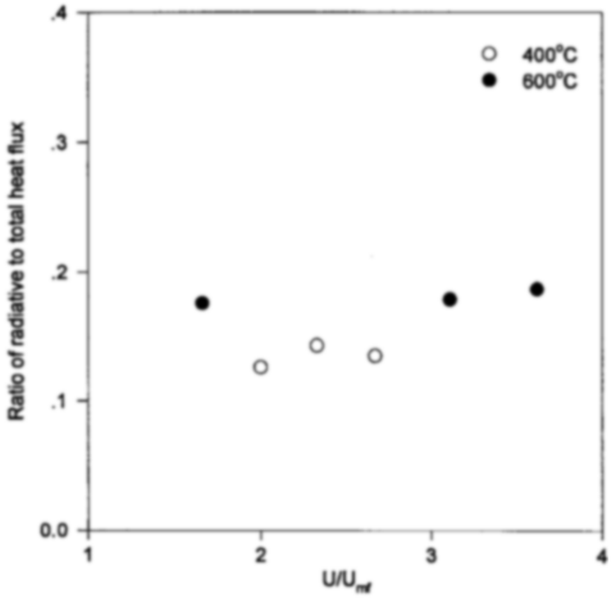

Fig. 7. Contribution of radiation to total heat transfer for sand particles.

bed temperature increased from 400°C to 800°C, the radiative heat transfer coefficient increased about 3 times, from 30 W/m^{2}K to 80 W/m^{2}K. The linear dependence of the radiative heat transfer coefficient on bed temperature was also reported by Basu [1978]. Mathur and Saxena [1987] obtained the radiative heat transfer coefficient of 15-22 W/m^{2}K at 642°C with 0.75 mm sand particle and Ozkaynak et al. [1983] obtained a radiative heat transfer coefficient of 25 W/m^{2}K at 400°C and 60 W/m^{2}K at 700°C with a 0.733 mm sand particle. Il'Chenko et al. [1968] also re-ported the experimental data of radiative heat transfer coefficients of 100-120 W/m^{2}K for 0.57 mm ZrO_2 particle at 950°C. Compared with other experimental data, the experimental data of this study seem somewhat higher values than other ones. However the radiative heat transfer depended on the bed temperature, particle diameter and particle emissivity, the scattering of experimental data is inevitable.

4. Radiation Contribution

Another important outcome of the experiment is the percentage of total heat flux due to radiation. The experimental results for bed temperatures of 400°C and 600°C with sand particle are shown in Fig. 7. As can be seen in Fig. 7, the percent radiation is approximately 13% and 18% at a bed temperature of 400°C and 600°C, respectively. These findings compare favorably with the experimental results of Ozkaynak et al. [1983] who also noted that the percent radiation is approximately 10% and 20% at bed temperatures 400°C and 600°C with 0.730 mm sand particles. However, significant differences of radiation contribution in the high temperature fluidized bed arose due to different experimental methods. Yoshida et al. [1974] with emissivity difference method and Kharchenko and Makhorin [1964] with spherical calorimeter method reported that the radiant heat transfer is not significant in the bed temperature of 500-1,000°C. On the other hand, Jolley [1949] reported that percentage radiation was 33-43% at the temperature ranges of 770-980°C with cylindrical calorimeter method and Il'Chenko et al. [1968] found the radiation contribution of 18-50% at the bed temperature of 430-1,430°C with radiometer probe. Between the two different methods (first one employed the spherical metal with different surface emissivity and second one employed the transparent window and heat flux transducer) to determine the radiative heat flux in a fluidized bed at high temperatures, the second method is widely used due to disadvantages of the first method [Han, 1992]. Bak et al. [1985] also investigated the radiation contribution determined by the difference of the heat transfer coefficients obtained at room temperature and high temperature and found that it was about 10% in the coal combustor of 800-950°C. It may not be very meaningful to compare the percentages of total heat flux due to radiation found in this study with the results of other reports due to the different methods used to determine the radiative component and the different sizes and types of particles used. The experimental results of this study showed that less than 20% contribution of radiation in the fluidized bed of moderate temperature ranges (400-600°C) and radiative heat transfer in the overall heat transfer process cannot be neglected.

CONCLUSIONS

The percentage of total heat flux due to radiation, total heat transfer coefficient, radiative heat transfer, and bed emissivity for sand particles were studied in order to determine the radiative transfer characteristics in high temperature fluidized beds. Radiation is found to be a significant part of the overall heat transfer process in high temperature fluidized beds. The radiative heat transfer coefficient increases with bed temperature and bed emissivity for sand particle determined around 0.8 to 0.9 at high temperatures. The significant contribution that radiative heat transfer makes in the overall heat transfer process in high temperature fluidized beds cannot be neglected.

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NOMENCLATURE

A : heat transfer surfaces of immersed tube [m^2]
h_i : water side heat transfer coefficient [W/m^{2}K]
h_o : bed to immersed tube heat transfer coefficient [W/m^{2}K]
h_r : radiative heat transfer coefficient [W/m^{2}K]
Nu : Nusselt number
Pr : Prandtl number
Q : heat flux from bed to immersed tube [W/m^2]
Q_r : radiative heat flux from bed to surfaces [W/m^2]
T_b : bed temperature [K]
T_i : inlet temperature of heat transfer tube [K]
T_o : outlet temperature of heat transfer tube [K]
T_w : surface temperature of heat transfer tube [K]
U_o : overall heat transfer coefficient [W/m^{2}K]

Greek Letters

ε_b : emissivity of bed
ε_w : emissivity of sensor surface

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