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Measurement of radiative heat transfer coefficient in a high temperature circulating fluidized beds

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Abstract−Experimental measurements of the radiative heat flux were made, and radiative heat transfer coefficients were determined for a circulating fluidized bed of sand particles of mean diameters of 137 and 264 microns. The bed used in this study measured 0.05 m in diameter. The heat transfer test section was 0.9 m long and located in the middle of CFB riser. Operating temperature was varied from 200-600 °C, and the gas velocity in the CFB riser varied from 6 m/s to 11 m/s. The suspension densities covered a range from 3 to 35 kg/m^3. Time-averaged radiative heat flux was directly measured with a radiometer. Radiative heat flux and suspension emissivity showed strong dependence on the suspension density. Particle size effect on suspension emissivity was observed. Experimentally determined suspension emissivities, which ranged from 0.3 to 0.85, were in good agreement with the predicted suspension emissivity based on independent scattering theory. The radiative heat transfer coefficients were determined from the measured radiative heat fluxes and were found to be well predicted by the Stefan-Boltzmann law. It was also found that for a dilute system, the prediction of suspension emissivity by Hottel and Sarofim, in conjunction with independent scattering theory of Brewster and Tien, showed good agreement with experimentally determined suspension emissivity.

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

INTRODUCTION

The advantages of circulating fluidized bed applications to chemical reactors and coal combustors are well known in the chemical industry. Relative to the dense or bubbling fluidized beds, this circulating fluidized bed permits retention of most of the heat transfer enhancement and eliminates the major portion of the pressure drop losses. Much of the existing data for heat transfer in circulating fluidized beds have been obtained at low temperatures [1] and only a few experimental data are available at high temperature circulating fluidized beds [2-4]. Furthermore, direct measurement of radiative heat flux is rare in spite of the significant role of radiation at high temperatures [5-8]. Recently, more and more processes have been conceived that require the use of fluidized beds at relatively high temperatures. A major obstacle to the efficient design and construction of these high temperature systems is the lack of understanding and the inability to model the complex heat transfer mechanisms between wall and suspension. This paper presents experimental data for radiative heat transfer in a high temperature circulating fluidized bed heat exchanger.

EXPERIMENT

The experiments were conducted in a high temperature circulating fluidized bed facility, a schematic diagram of which is shown in Fig. 1. The circulating fluidized bed was 2.36 m long and the bed diameter was 0.05 m and the test section for radiative heat transfer was a shell and tube type heat exchanger with an ID of 0.05 m, OD of 0.07 m and 0.91 m long. The superficial gas velocity was between 5 m/s to 11 m/s at operating temperatures and the different sizes of silica sand particles (136 and 264 μm) were used. The bed temperature was controlled by the natural gas combustion at the bottom of the bed and the addition of secondary air. The solid circulation rate was measured by the accumulation rate of particles in the particle reservoir at the bottom of the cyclone. Suspension density was deduced from a pressure drop gradient and it was in the range of 3 kg/m^3 to 35 kg/m^3. The radiative heat flux was measured by a radiometer and the details of fabrication, principle of measurement and calibration of this radiometer was given in Han et al. [8].

RESULTS AND DISCUSSION

1. Emissivity of Particle Suspension

In radiative heat exchange between a hot gas-solid suspension and cold wall, radiative heat flux can be estimated by treating the suspension as a gray body.

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

During the current experiments, radiative heat flux was directly measured between the suspension and radiometer sensor surface in which emissivity was close to unity.

Therefore, Eq. (1) can be approximated as follows:

$$q_r = \varepsilon_b \sigma(T_b^4 - T_w^4) \tag{2}$$

From Eq. (2), emissivity of the fluidized bed was determined by the measured q_r, T_b and T_w. Emissivity derived from Eq. (2) is the sum of gas emissivity and suspension emissivity. To obtain the

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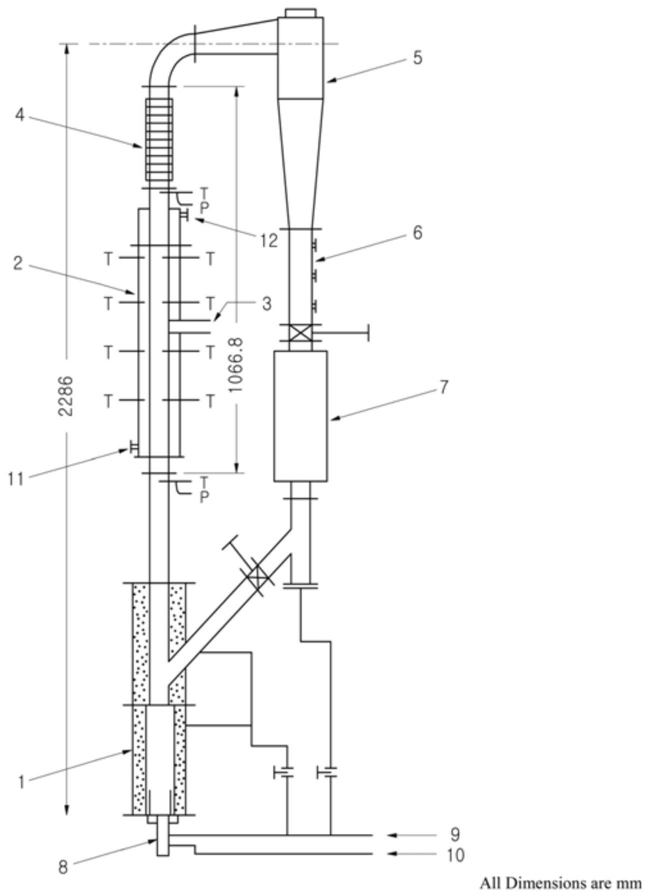

Fig. 1. Schematic diagram of test facility.

1. Combustion chamber
2. Heat transfer test section
3. Radiation probe
4. Thermal expansion joint
5. Cyclone
6. Return column
7. Particle reservoir
8. Gas burner
9. Air
10. Natural gas
11. Cooling water in

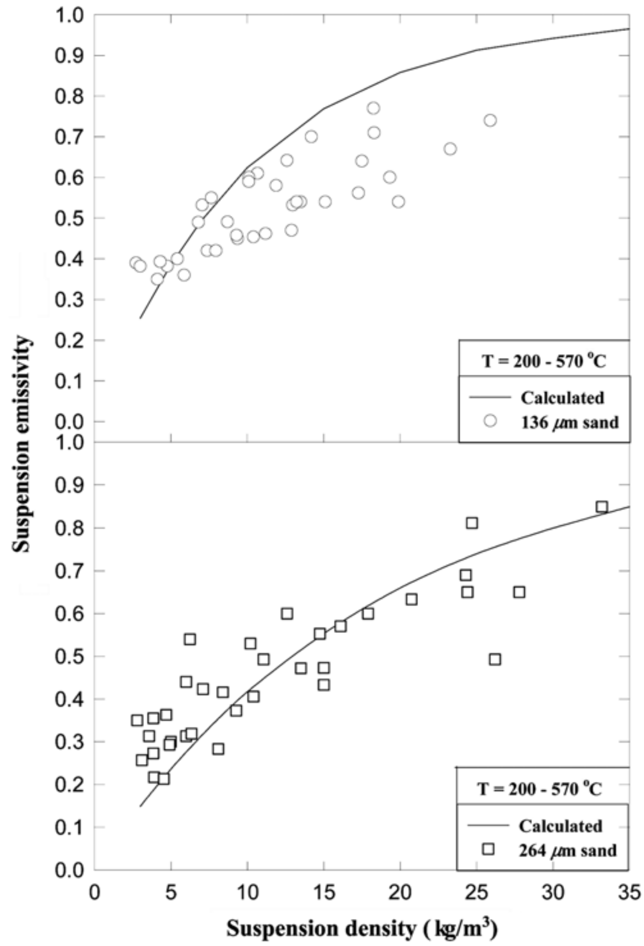

Fig. 2. Experimentally determined emissivity with calculated suspension emissivity.

suspension emissivity, the contribution of gas emissivity by water vapor and carbon dioxide was subtracted from the calculated bed emissivity ε_b. Since suspension emissivity is a major parameter in predicting the radiative heat flux for high temperature circulating fluidized beds, the experimentally determined suspension emissivity was compared with the predictive equation given by Hottel and Sarofim [9].

$$\varepsilon_{sus}=1-e^{-kL} \tag{3}$$

where L: characteristic length, k: extinction coefficient

Glicksman [10] recommended L=0.88 D for the determination of characteristic length in cylindrical fluidized beds. For predicting the extinction coefficient k, Brewster and Tien [11] suggested using the independent scattering theory for low suspension density ranges (dilute system).

$$k=\frac{1.5\varepsilon_p f_v}{d_p} \tag{4}$$

The comparison of experimentally determined emissivity with the model Eq. (3) for the two different sizes of sand particles is given in Fig. 2. The increase in suspension emissivity with suspension density is believed to be due to increased absorption area per unit volume of suspension. For the smaller size particle, the model equation overestimated the emissivity by about 20%, but predicted the increasing trend for emissivity with suspension density with reasonable accuracy. For the 264 μm sand particles, the model equation showed good agreement with experimental data. As expected from Eqs. (3) and (4), smaller particles have a higher emissivity than larger ones at the same suspension density and temperature. This can be explained by the fact that smaller particles have larger radiation absorption area than the larger ones at the same suspension density. Kobro and Brereton [12] supported this same trend in terms of a radiative heat transfer coefficient. Basu [2] also experimentally measured the suspension emissivity, and it varied between 0.7 to 0.85 for the suspension density of 15 to 40 kg/m^3 with the 296 μm sand particle. Fig. 3 shows the effect of characteristic length on suspension emissivity. As shown in Fig. 3, Basu's [2] experimental results of suspension emissivity are higher than this study. An explanation of this difference in suspension emissivity for similar size particles can be found from the Eq. (3). Experimental data of Basu [2] were obtained in a bed of 0.2 m in diameter and the current tests used a smaller bed (0.05 m), resulting smaller characteristic length and smaller suspension emissivity for the present tests. Therefore, a combina-

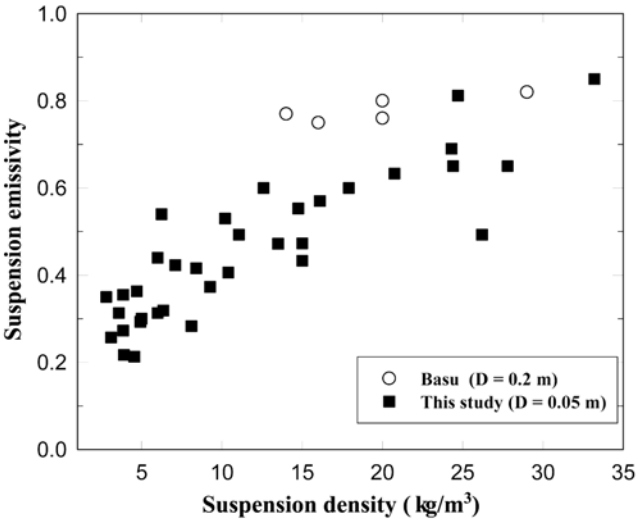

Fig. 3. Characteristic length effect on suspension emissivity.

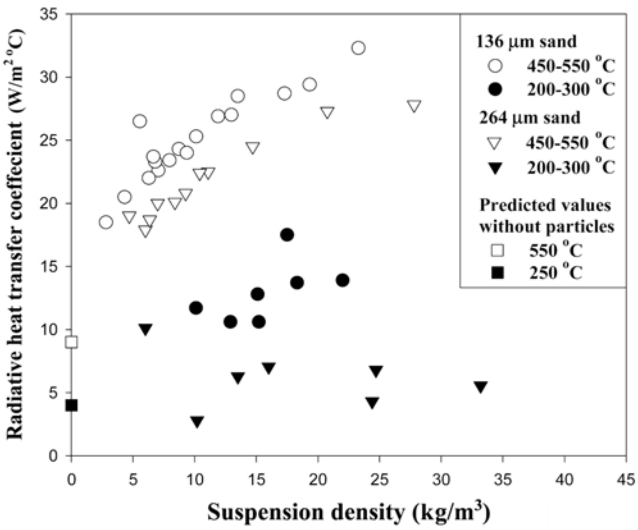

Fig. 4. Radiative heat transfer coefficient vs suspension density.

tion of Eqs. (3) and (4) is useful to predict the suspension emissivity in the circulating fluidized bed.

2. Radiative Heat Transfer Coefficient

The calculated radiative heat transfer coefficient h_r is defined as shown in Eq. (5).

$$h_r = \frac{q_r}{(T_{sus} - T_w)} \tag{5}$$

Variation of h_r with suspension density is shown in Fig. 4. As mentioned before, the radiative heat transfer coefficient increased with suspension density because of increased suspension emissivity. Effect of suspension temperature is shown in Fig. 5 where radiative heat transfer coefficients are plotted at various operating suspension temperatures. It can be seen that the radiative heat transfer coefficient is strongly affected by the suspension temperature, increasing from 10 W/m² °C to approximately 33 W/m² °C as the suspension temperature increased from 200 °C to 550 °C.

The experimentally determined radiative heat transfer coefficients

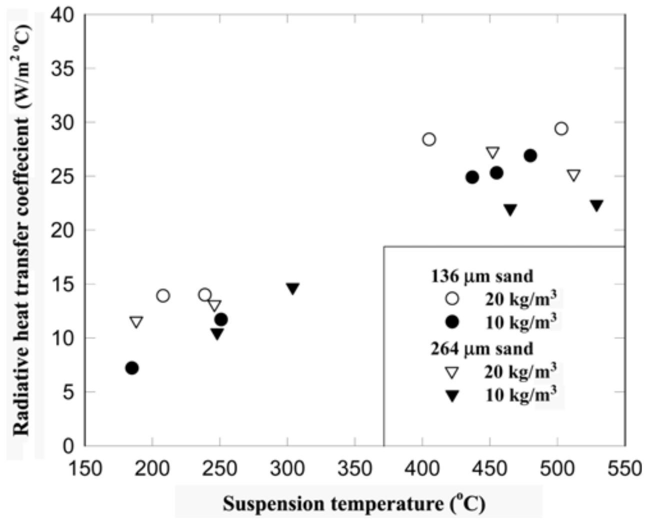

Fig. 5. Radiative heat transfer coefficient vs suspension temperature.

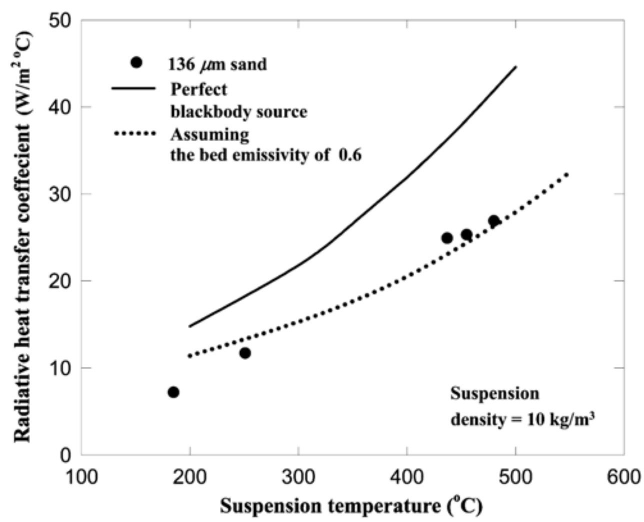

Fig. 6. Comparison of theoretical and experimental values of radiative heat transfer coefficients.

were compared with theoretical values calculated from Eq. (1). Fig. 6 shows the comparison of experimentally determined radiative heat transfer coefficients with these predicted values. The solid line in Fig. 6 represents the theoretical values by assuming that suspension emissivity and bed emissivity are unity. The dotted line represented the theoretical radiative heat transfer coefficients by assuming that suspension emissivity is 0.6 and bed emissivity is unity. From the Fig. 6, it can be said that the experimentally determined suspension emissivity which was deduced from the measured radiative heat flux by the radiometer reasonably agreed with theoretical values. This result also confirmed that the radiometer technique is a reasonable experimental device for the measurement of radiative heat flux in the circulating fluidized bed as reported by Luan et al. [6].

CONCLUSIONS

Total and radiative heat flux were obtained simultaneously in a circulating fluidized bed heat exchanger at temperatures of 200-600 °C for two different sizes of silica sand particle. In a circulating fluidized bed system, the bed emissivity was found to be the important factor in determining the radiative heat flux. For a dilute system, the prediction of suspension emissivity by Hottel and Sarofim, in conjunction with independent scattering theory of Brewster and Tien, showed good agreement with experimentally determined suspension emissivity. At the same suspension density, smaller particles have a higher suspension emissivity than the larger ones because of a lower extinction coefficient. The radiative heat transfer coefficient increased with suspension density and suspension temperature as expected from the radiative heat flux equation.

NOMENCLATURE

d_p : particle diameter [μm]
D : bed diameter [m]
f_v : solid volume fraction
h_r : radiative heat transfer coefficient [w/m^2 °C]
k : extinction coefficient [1/m]
L : characteristic length [m]
q_r : radiative heat flux [w/m^2]
T_b : bed temperature [°C]
T_{sus} : suspension temperature [°C]
T_w : wall temperature [°C]

Greek Letters

ε_b : bed emissivity
ε_p : single particle emissivity
ε_{sus} : suspension emissivity
ε_w : wall emissivity
σ : Stefan-Boltzmann constant
ρ_{sus} : suspension emissivity

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