Experimental Measurement of Radiative Heat Transfer in Gas-Solid Suspension Flow System

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An experimental measurement of the radiative heat flux from a gas-solid suspension to wall was made in a water cooled heat exchanger. The heat-transfer test section was 5 cm ID and 90 cm long. Operating temperature ranged from 200 to 600°C and the gas velocity at the inlet of the test section varied from 6 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 using a radiometer, which allowed to determine suspension emissivity using a measured suspension temperature. Radiative heat flux and suspension emissivity showed strong dependence on the suspension density. The effect of particle size on suspension emissivity was also studied by using two different sizes of particles. Experimentally determined suspension emissivities, which ranged from 0.3 to 0.85, agreed well with the predictable suspension emissivities based on an independent scattering theory. The contribution of radiation to total heat transfer was about 40−50% for the operating condition used in this study.

Introduction

It is a known fact that gaseous convective heat transfer is enhanced by the addition of particles in the gas flow. The subject of heat transfer in particulate flows came into scientific prominence during the 1950s as a heat-transfer augmentation technique. Experimental work by Farber and Morley (1957), Farber and Depew (1963), and Tien (1961) established a database and experimental correlations for convective heat-transfer coefficients of air-solid mixtures. Recently, heat transfer in gaseous-particulate flow was of great interest in fluidized-bed applications. Much of the existing data for gas-solid suspension flows have been obtained at relatively low temperatures. A major obstacle to the efficient design and construction of high-temperature gas-solid suspension heat exchangers is the lack of understanding and modeling of the complex heat-transfer mechanisms. At high temperatures, in addition to conduction and convection which are the dominant heat-transfer mechanisms at low to moderate temperatures, thermal radiation becomes important. A demand has grown, therefore, for a model which considers all three mechanisms of heat transfer in a gas-solid suspension flow system. Recently, experimental and theoretical study of suspension emissivity was carried out for the radiation contribution in a high-temperature fluidized bed and circulating fluidized bed. Han and Cho (1999) and Lee et al. (1999) measured the suspension emissivity in a circulating fluidized-bed coal combustor and bed emissivity in a high-temperature bubbling fluidized bed with the radiometer, respectively. Baskakov and Lecker (1997) also suggested the theoretical methods of estimating the effective emissivity of a gas-particle suspension. The objectives of the present work are to provide experimental data of radiative heat transfer, and to investigate parametric effect of temperature and suspension density on suspension emissivity.

Experimental Studies

The experiments were carried out in a high-temperature heat exchanger facility, which is shown in Figure 1. The test section was a shell-and-tube type heat exchanger with an ID of 5 cm, OD of 7.5 cm, and 90 cm long. A commercially available gas burner was used to heat the particles. A cyclone was

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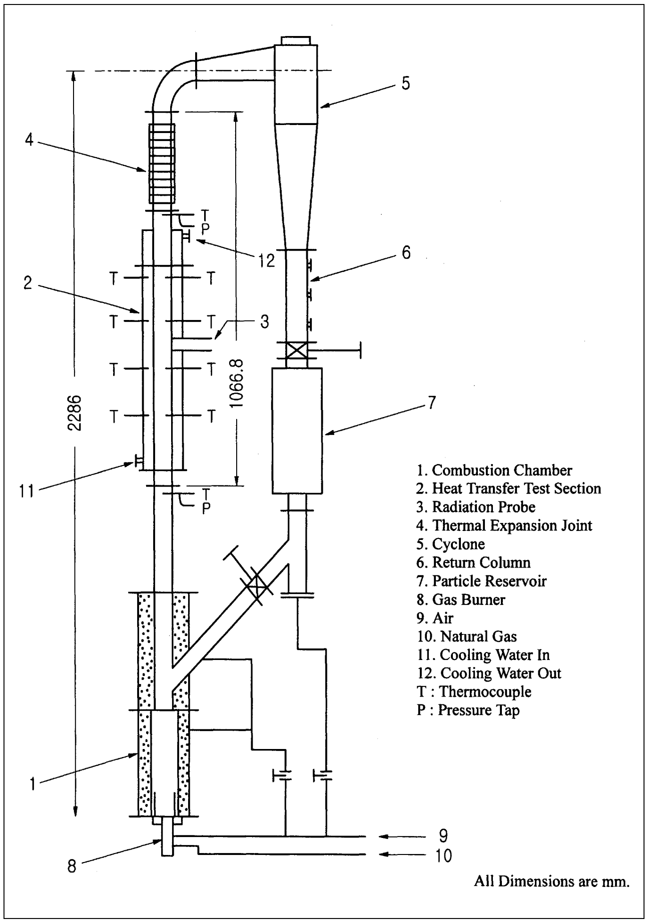

Figure 1. Heat-transfer test facility.

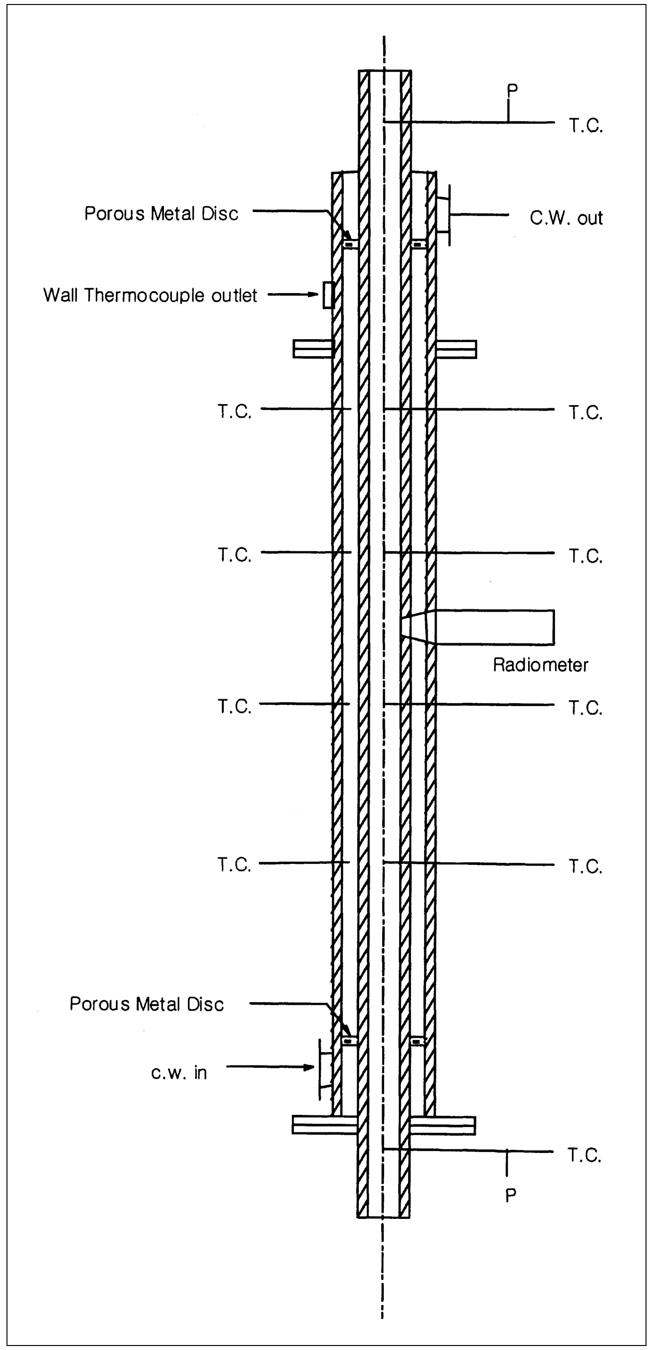

Figure 2. Heat-transfer test section.

used as a gas-solid separator, and the captured particles were recirculated through the particle reservoir. Solid circulation rate was measured by temporarily closing the quick closing gate valve located at the top of the particle reservoir and timing the accumulation of a packed bed of solids through three 15.1 mm OD quartz sight windows mounted along the return column. An inventory of solid particles in the lower particle reservoir prevented any interruption of particle feed to the test section. The particle feed rate to the heat exchanger was controlled by adjusting the opening of the feed valve and by regulating the secondary air injection flow rate through the solid feeding line. This secondary air injection flow allows particles to flow down smoothly and prevents the back flow of gas through the return line. The test section is instrumented with two pressure taps at the bottom and the top of the test section, as shown in Figure 2, to monitor the suspension density. Thermocouples are installed to measure temperatures of suspension, wall, and cooling water. Suspension temperatures are measured at six locations along the test section, as shown in Figure 2. Wall temperatures are measured at four locations along the test section by brazing 1.0 mm O.D. shielded thermocouples onto the tube outside. Two additional thermocouples were used to measure inlet and outlet temperature of the cooling waters. In the middle of test section, a radiation probe was mounted to measure the radiative heat flux. Two different sizes of silica sand particles were used. Particle-size distribution, as measured by sieve analysis and some physical properties for these particles, is shown in Table 1. The superficial gas velocity varied between 5 m/s to 11 m/s at operating temperatures. Suspension density, which was deduced from a pressure drop gradient, covered a range from 3 kg/m^3 to 35 kg/m^3.

Because of the inherent fluctuating motion of gas-solid suspension flow, a data acquisition system was employed to measure the time average suspension density, radiative heat flux, and temperature profiles. In general the data were recorded at every 5 s and averaged over 600 s.

Table 1. Particle-Size Analysis and Fluidization Properties for the Test Silica-Sand Particle

Size Range (μm)	Sand No. 1 (wt. %)	Sand No. 2 (wt. %)
425+	—	—
425–355	0.011	—
355–297	0.279	—
297–250	0.336	—
250–212	0.221	—
212–180	0.103	0.0234
180–150	0.019	0.341
150–120	0.0137	0.299
120–105	0.007	0.1589
105–90	0.005	0.1338
90–53	—	0.0437
Mean particle size, μm	264	137
Particle dens., kg/m^3	2,650	2,650
Terminal vel.* at room temp., m/s	2.05	1.09

*Terminal velocity was calculated from the information of Kunii and Levenspiel (1969).

Design and Calibration of Radiation Probe

There are two widely used methods to determine the contribution of radiation to heat transfer in a fluidized bed at high temperature. One of these methods employs small spherical metal probes with different surface emissivities (Botterill et al., 1984). In this method, the difference in heat transfer between a black surface and a white one is attributed to radiation. The uncertainties in the emissivities and effects of varying surface temperatures could lead to underestimation of radiative flux. The other method, employing the direct detection of radiation by use of radiometers (Ozhaynak et al., 1983), is subject to difficulties with the transparent windows. Such windows are necessary to prevent particle impingement on the radiometers, but could cause errors in interpretation of the measurements. During the present experiment, the radiometer probe was selected over the method which utilizes the change in radiation due to surface emissivity. The disadvantages of this method were eliminated by proper cooling of the window and choosing a window material with a wide range of transmittance and a high thermal conductivity. Because of the above difficulties in measuring radiative heat flux, a careful design and fabrication of the radiation probe were necessary. The basic components of the radiometer probe were the brass body, the ZnSe window, and the heat flux transducer. Detailed dimensions of the radiometer are shown in Figure 3. A heat flux transducer with a 3.175 mm OD sensing area was water cooled. It was manufactured by Medtherm Co. It functions according to the theory and principle of a simple thermopile. An instrument operating on these principles will provide a direct readout in millivolts proportional to incident heat flux. The transducer consisted of an insulating wafer with a series of thermocouples with consecutive thermoelectric junctions on opposite sides of the wafer. This assembly was bonded to a heat sink to assure heat flow through the sensor. Heat received on the exposed 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 is across the wafer and, thus, the output signal was directly proportional to the heat flux. Coolant water flowed into the heat flux transducer through a 3.175 mm OD tube in order to maintain the temperature of the heat sink constant and it is below that of the sensor surface. The response time of the transducer was 200 ms. In the selection of the window material, consideration was given to the operating temperatures and to the wavelength transmittance in the temperature range of this experiment. Among the several candidates, the Zinc Selenide (ZnSe) window was employed. It reasonably transmits radiation well between 0.5 to 20 μm, which is good for the entire range of operating temperatures. This will be discussed later. The radiometer probe was bench-calibrated using a black-body source. When placed in the test section, the amount of radiant heat flux incident on the probe surface at various operating conditions could thus be measured. The radiation probe was placed inside of disc type cooling water jacket so that conditions were similar to those which occur when the probe was placed in the test section. During the calibration, the radiation probe was placed as close as possi-

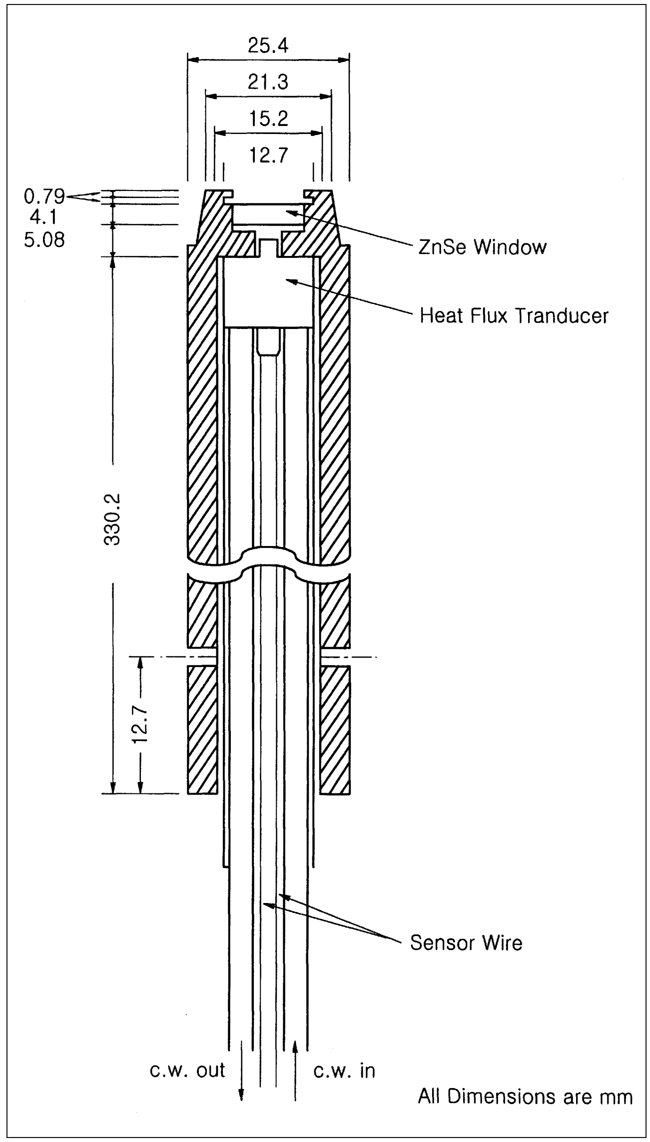

Figure 3. Dimension of radiation probe.

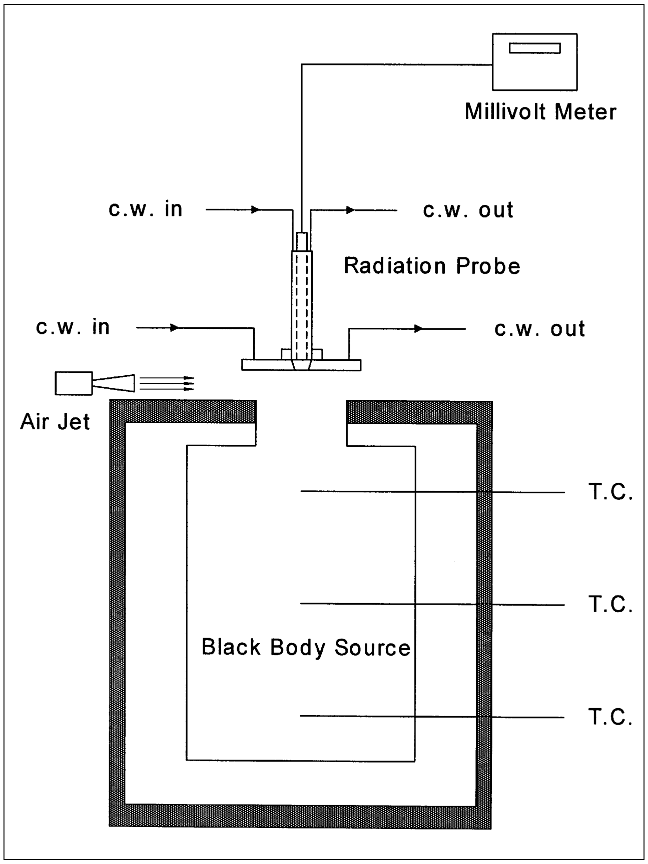

Figure 4. Calibration devices for radiation probe.

ble to the front of the opening of the blackbody source, a controlled furnace, as shown in Figure 4. One of the complications of having the furnace and probe close together is that natural convection may play a part in heating the sensor surface. One way of avoiding this is to blow a stream of cold air across the upper surface of the furnace. For this reason, a flute-like air blowing system was mounted between the radiometer probe and furnace such that the air flow was perpendicular to the axis of the furnace. Hence, any convective heat effect was eliminated. The electromotive force (emf) readings of the heat flux transducer and the corresponding temperature of the furnace were recorded for temperatures from 300 to 800°C using the temperature at the bottom of the furnace. Figure 4 illustrates the calibration setup of the radiation probe. The ideal blackbody radiant heat flux was calibrated from the Stefan-Boltzman equation. The best curve fit of the emf readings vs. blackbody radiant heat flux was determined. This best curve fit is linear, as shown in Figure 5. The transmissivity of a ZnSe window was needed for the determination of the radiative heat flux. Transmissivity is defined as the fraction of incident radiation that is transmitted by the ZnSe window. Transmissivity was measured experimentally as a function of blackbody source temperature by dividing the detector output signal with the window in place by the detector output without the window. The results plotted vs. source temperature in Figure 6 shows that the transmissivity is about 0.64 and is independent of blackbody source temperature for the range studied.

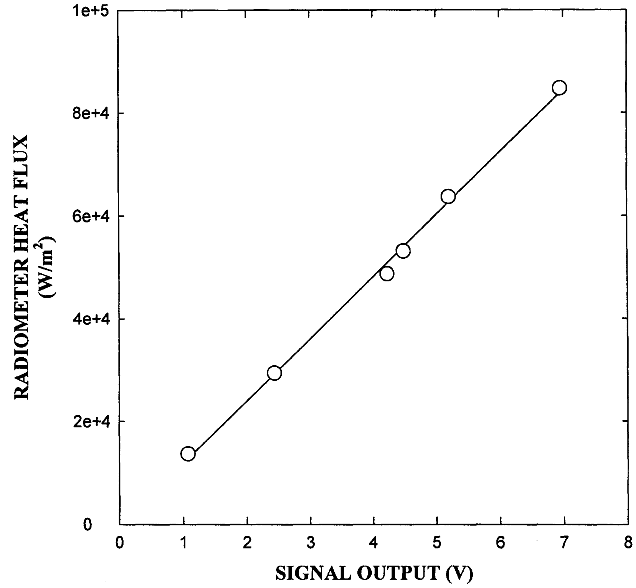

Figure 5. Calibration curve for radiometer.

Results and Discussions

During the heat-transfer experiment in the circulating fluidized bed, the heat-transfer coefficient ht was calculated by measuring the heat flux from the suspension to cooling water wall. In this calculation, the suspension to the wall heat-transfer coefficient is determined by subtracting the water side resistance. In order to remove the error which might occur in calculating the water side heat-transfer coefficient, direct measurement of suspension to wall heat transfer was made by measuring the temperature of the heat-transfer surface as mentioned in the experimental section.

Figure 7 showed the measured suspension to wall heat-transfer coefficient (h_t) a function temperature at the sus-

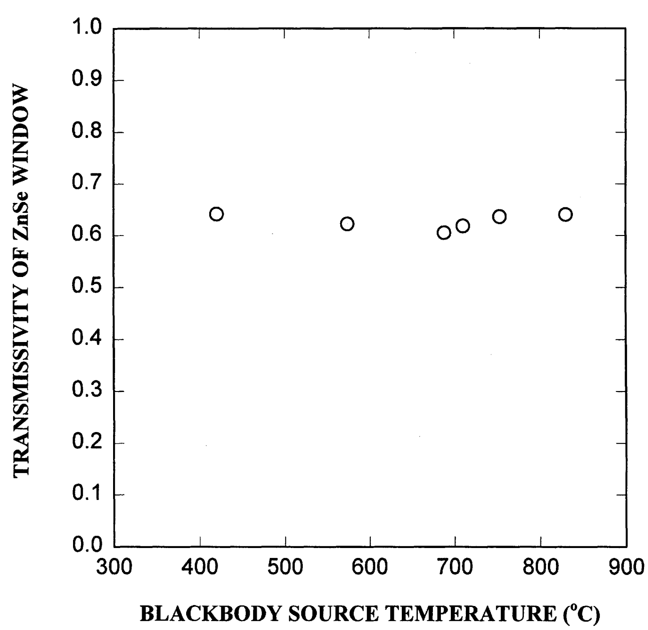

Figure 6. Transmissivity of ZnSe window.

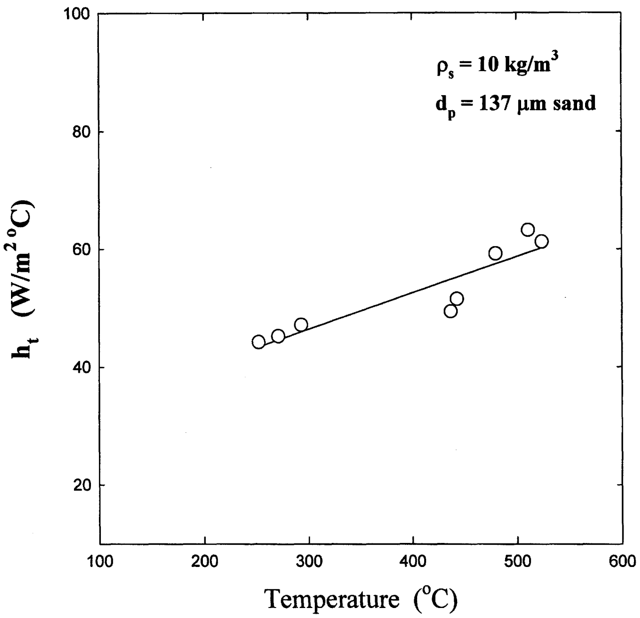

Figure 7. Suspension to wall heat-transfer coefficient as a function of temperature.

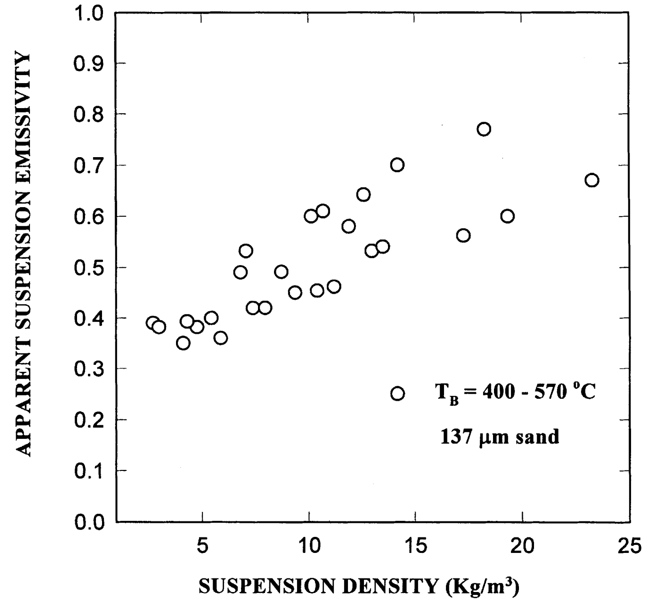

Figure 8. Suspension emissivity as a function of suspension density.

pension density of 10 kg/m^3 for 137 μm sand particle. As can be seen in Figure 7, the heat-transfer coefficient increased with temperature. It is believed that suspension to wall heat transfer is the sum of particle convection, which is strongly dependent on the suspension density and radiation. Since the suspension density was almost constant for this experiment, the increase of the heat-transfer coefficient results from the radiation of suspension.

The emissivity of gas-solid suspension in the circulating fluidized bed was determined by the radiometer and the parametric study of radiative properties of suspension is analyzed in detail in this section.

Emissivity of gas-solid suspension

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

$$q_r = \frac{\sigma\left(T_{\text{sus}}^4 - T_w^4\right)}{\dfrac{1}{\epsilon_{\text{sus}}} + \dfrac{1}{\epsilon_w} - 1} \tag{1}$$

In the present experiments, radiative heat flux was directly measured between the suspension and the radiometer sensor surface in which emissivity was close to unity. Therefore, Eq. 1 can be approximated as follows

$$q_r = \epsilon_{\text{sus}}\sigma\left(T_{\text{sus}}^4 - T_w^4\right) \tag{2}$$

From Eq. 2, emissivity of the suspension was determined by the measured q_r, T_{sus} and T_w. Since the emissivity calculated from Eq. 2 is the sum of gas and suspension emissivities, the gas emissivity contribution by water vapor and carbon dioxide was subtracted. Figure 8 shows the measured suspension emissivity as a function of suspension density for 137 μm silica sand particles at different temperature ranges. It is clear that suspension emissivity increases with suspension density and suspension temperature does not significantly affect the suspension emissivity. Therefore, the radiative heat flux should increase with suspension density. This finding can be explained that the dense suspension has the larger absorption (emission) area per unit volume of suspension. The particle-size effect on suspension emissivity is shown in Figure 9. As seen in Figure 9, smaller particles have higher suspension emissivity than that of larger particles at the same suspension density and temperature because of the larger radiation ab-

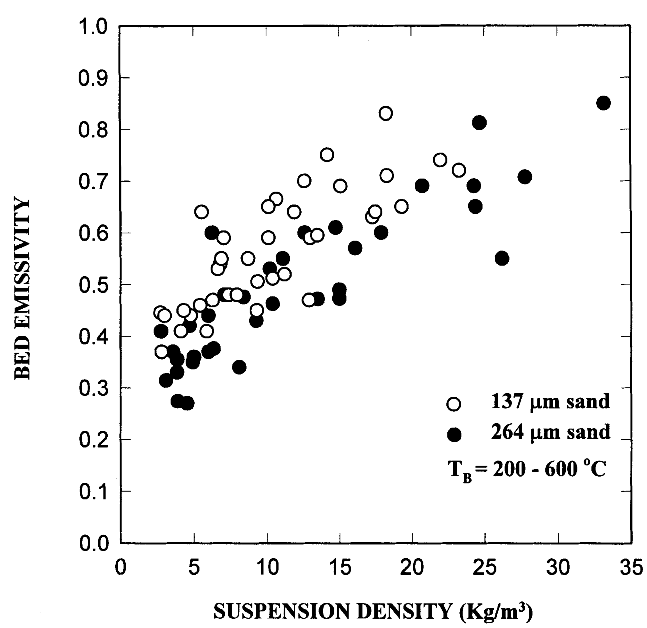

Figure 9. Particle-size effect on suspension emissivity.

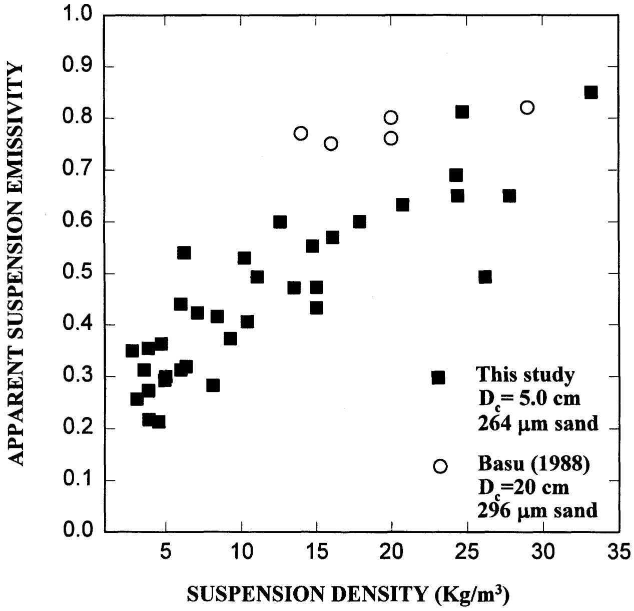

Figure 10. Effect of bed diameter on suspension emissivity.

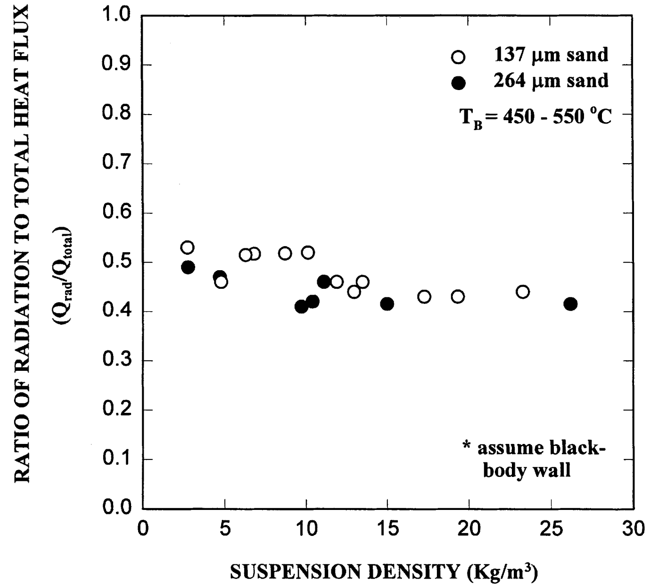

Figure 11. Ratio of radiation to total heat-transfer vs. suspension density for different sizes of sand particles.

sorption (emission) area of the smaller particles. Kobro and Brereton (1986) reported the same trend in terms of radiative heat-transfer coefficient.

It is also known that the suspension emissivity of a circulating fluidized bed is also function of path length L. For a long cylindrical riser, the path length L is about 90% of the bed diameter (Baskakov and Leckner, 1997). Figure 10 showed the bed diameter effect on the suspension emissivity in a circulating fluidized bed. Basu (1988) measured the suspension emissivity with a radiameter in a high temperature circulating fluidized bed of 20 cm diameter. As can be seen in Figure 10, at the same particle size and suspension density, suspension emissivity showed a higher value for the larger diameter of the bed. Baskakov and Leckner (1997) reported that suspension emissivity rapidly approaches unity as the bed diameter becomes larger than 20 cm. Therefore, for larger commercial units, the suspension emissivity approaches unity at a much smaller suspension density.

Contribution of Radiation to Total Heat Flux

It is interesting to know the ratio of radiative heat flux to total heat flux in a high-temperature gas-solid suspension flow heat exchanger system. In Wu's (1989) experiment of a circulating fluidized-bed combustor, the fraction of the total transfer due to radiation varied from 50% to 30% as suspension density increased from 15 to 60 kg/m^3 at the bed temperature of 587°C. Basu (1988) also conducted the high-temperature heat-transfer experiment in a circulating fluidized-bed combustor and found that the ratio of radiative to total heat-transfer coefficients was about 30% at 500°C and 20 kg/m^3 suspension density. In this work, the ratio of radiative to total heat flux was plotted as a function of suspension density at the average suspension temperature of 550°C. Figure 11 plotted the ratio of radiative to total heat flux as a function of suspension density for two different sizes of sand particles.

The experimentally determined contribution of radiation to total heat transfer was observed from 55% to 40% as the suspension density increased from 5 to 25 kg/m^3. The decreasing trend of contribution of radiation to total heat transfer with increasing suspension density can be explained due to domination of particle convective heat flux as suspension density increases. In comparison with bubbling fluidized-bed systems, Il'chenko (1968) and Ozkaynak et al. (1983) experimentally found by using radiometer that the radiation accounts for about 20% of the total heat transfer at a bed temperature of 500°C, and Lee et al. (1999) experimentally obtained the 13% and 18% of contribution of radiation to total heat transfer for 260 μm sand particles at a bed temperature of 400°C and 600°C, respectively. The experimental results of the present study showed that, in a circulating fluidized bed of moderate temperature ranges (400–600°C), the radiative heat transfer is the most significant heat-transfer process and the radiative properties should be considered in designing the circulating fluidized-bed system.

Conclusions

Total and radiative heat flux were obtained simultaneously in a gas-solid suspension flow heat exchanger at temperatures of 200–600°C for two different sizes of silica sand particle. The experimentally determined suspension emissivity has strong dependency on suspension density. At the same suspension density, smaller particles have a higher suspension emissivity than the larger one. In a dilute particulate flow system (low suspension density range), the contribution of radiation to total heat transfer was about 30–50% at 600°C. It can be said that the dominant heat-transfer mechanism in the dilute suspension system was radiation, which was a minor factor in the bubbling fluidized bed at a temperature of 500°C.

Notation

h_t = suspension to wall heat-transfer coefficient ($W/m^2 \cdot K$)
q_r = radiative heat flux (W/m^2)
T_B = bed temperature (K)
T_{sus} = suspension temperature (K)
T_w = wall temperature (K)
ϵ_{sus} = suspension emissivity
ϵ_w = wall emissivity
σ = Stefan-Boltzman constant
ρ_{sus} = suspension emissivity

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