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Experimental research of radiative heat transfer in fluidized beds

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Abstract—A new method to measure the radiative heat transfer in fluidized beds was presented. Experiments were carried out on a $0.8\,\mathrm{t\,h^{-1}}$ fluidized bed combustion boiler. The residual slag of fired coal was operated in a fluidized bed at room temperature. As the radiative heat transfer at room temperature is insignificant, its contribution at high temperatures might be obtained by the comparison of experimental results at high and low temperatures. On experimental study, a radiative contribution was given as a function of bed temperature and particle size. The results were compared with those in other references.

1. INTRODUCTION

THE RESEARCH of radiative transfer in a fluidized bed is insufficient. There is no unanimous opinon on the radiative contribution. Earlier research [1–3] indicated that the radiative heat transfer in a fluidized bed could be neglected at bed temperatures below 600°C. In the conclusion of Kharchenko's paper [4], radiation is neglected even at temperatures over 1000°C.

Other investigators theoretically analysed the radiative heat transfer in a fluidized bed. Different models were made to describe the radiative contribution. Based on Vedamurthy's model [5], the radiative contribution is predicated as 13–17% at a bed temperature of 900°C when the particle diameter $d_s = 0.5$ mm. But Wright [6] deduced that the radiative contribution is 30–50% at a bed temperature between 850 and 900°C. In the conclusion of ref. [7] it is about 18–32% at a bed temperature of 800–1000°C.

Recently a large amount of experimental research on radiative heat transfer in fluidized beds has been undertaken. Vadival [8] designed a radiative calorimeter using a thermal resistor, which was used to measure the variation of the radiative heat transfer coefficient around the tube immersed in the fluidized bed. The experiments proved that the radiative contribution is about 35% at a bed temperature of 750°C. By the application of another kind of calorimeter, in which a constantan plank was used as an endothermic element, Zhang Hesheng's experiments [9] show that the radiative contribution increases from 20 to 30% with a bed temperature increase from 800 to 1050°C.

In this paper, an indirect measuring method is introduced. The total heat transfer coefficient from the high temperature bed to the water cooling tube was measured in a fluidized bed boiler. The residual slag of fired coal was then operated at room temperature in the same kind of fluidized bed. Consequently, the particle diameter is assumed to be the same. The radiative heat transfer at room temperature is inconsiderable. According to the modelling conditions, the fluidization heat transfer coefficient (total heat transfer except radiation, including gas convection and particle conduction) at high temperatures can be deduced from the experiments at room temperature, and the radiative contribution is thus obtained.

2. MODELLING CONDITIONS

Heat transfer due to gas convection and particle conduction is related to many factors. A detailed analysis for these factors is complex. However, we can deduce the fluidization heat transfer coefficient at high temperature from a cold experiment, if the modelling conditions of two states are the same, i.e. all dimensionless numbers related to heat transfer must keep the same value. Of course it is difficult to meet all of these requirements, we may have to make a choice among them, based on the mechanism of heat transfer.

Convective heat transfer from a gas to a tube immersed in a fluidized bed is undoutedly related to Reynolds number and Prandtl number, which appears in almost all correlations of gas convective heat transfer in fluidized beds. But also the movement of particles would affect heat transfer in a fluidized bed and therefore, the Archimedes number will be important for the description of the heat conduction of particles. Besides, porosity, ε, indicates the extent of fluidization. The particle heat conduction decreases with porosity, while porosity is affected by the gas flow rate.

Grewal [10] recently considered the effect of volumetric heat capacity ($\rho_s C_{ps}$) and introduced a dimensionless number ($\rho_s C_{ps} D^{3/2} g^{1/2}/K_f$) in his correlation.

Hence, Reynolds number, Prandtl number, porosity of fluidized bed, Archimedes number and the dimensionless number introduced by Grewal are considered

NOMENCLATURE

- A cross-sectional area of fluidized bed [m^2]
- Ar Archimedes number [dimensionless]
- C_p specific heat [J kg^{-1} °C^{-1}]
- D diameter of immersed tube [m]
- d_s diameter of solid particles [m]
- F heat transfer area of immersed tube [m^2]
- G gas flow rate [N m^3 h^{-1}]
- g gravitational acceleration [m s^{-2}]
- h heat transfer coefficient between bed and tube [W m^{-2} °C^{-1}]
- h_r radiative heat transfer coefficient [W m^{-2} °C^{-1}]
- h_t total heat transfer coefficient at high temperature [W m^{-2} °C^{-1}]
- K thermal conductivity [W m^{-1} °C^{-1}]
- N heating electric power [W]
- Nu Nusselt number [dimensionless]
- Pr Prandtl number [dimensionless]
- Q flow rate of cooling water [kg s^{-1}]
- Re Reynolds number [dimensionless]
- T temperature [K]
- u fluidizing velocity [m s^{-1}].

Greek symbols
- ε voidage of fluidized bed
- ν viscosity [N m^{-1} s^{-1}]
- ρ density [kg m^{-3}].

Subscripts
- b fluidized bed
- c cold state (at room temperature)
- f fluidized gas, air
- h hot state (at high temperature)
- s solid particle, coal
- w wall of immersed tube.

as the most important numbers. All of these numbers must remain the same in cold and hot experiments.

The investigations of Vreedenberg [11] and Andeen [12] gave the dimensionless relation of fluidization heat transfer, in which Re and Ar appear in the form of (Re/Ar). So, the first requirement of modelling experiments is

$$(Re/Ar)_c = (Re/Ar)_h. \quad (1)$$

The particles operated in cold experiments are the residual slag of fired coal in a fluidized bed boiler. The average diameter and density of particles can be assumed the same as in experiments at high temperature, then equation (1) becomes

$$u_c = \frac{(\rho_f \nu_f D)_h}{(\rho_f \nu_f D)_c} u_h. \quad (2)$$

That is, to keep the modelling condition (1), the air flow rate in cold experiments has to be determined by

$$G_c = \frac{A_c}{A_h} \frac{(\rho_f \nu_f D)_h}{(\rho_f \nu_f D)_c} \frac{T_{bh}}{T_{bc}} G_h. \quad (3)$$

Another fundamental modelling requirement is

$$\varepsilon_c = \varepsilon_h. \quad (4)$$

Modelling conditions (3) and (4) must be satisfied simultaneously. But there is only one variable, the air flow rate. Fortunately, the cold experimental results at room temperature (Fig. 1) show that at a considerable range of air flow rates near the optimal value the heat transfer coefficient is almost constant. And in modelling experiments, when the particles were appropriately fluidized relation (4) was satisfied. The air flow rate is about 1000 N m^3 h^{-1} which is near the optimal value,

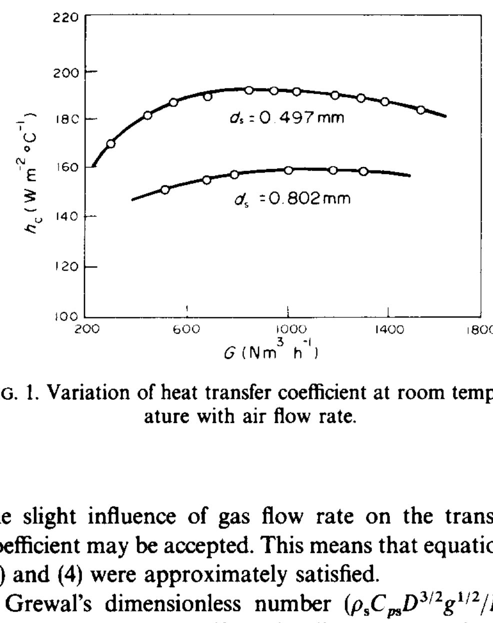

FIG. 1. Variation of heat transfer coefficient at room temperature with air flow rate.

the slight influence of gas flow rate on the transfer coefficient may be accepted. This means that equations (3) and (4) were approximately satisfied.

Grewal's dimensionless number $(\rho_s C_{ps} D^{3/2} g^{1/2}/K_f)$ may be kept constant if a tube diameter was chosen as

$$\frac{D_h}{D_c} = \left(\frac{(K_f)_h}{(K_f)_c} \frac{(C_{ps})_c}{(C_{ps})_h}\right)^{2/3} \quad (5)$$

If the temperature in the fluidized bed is about 800°C and the room temperature is 40°C, equation (5) requires

$$D_c = 0.7 D_h.$$

The diameter of the tube set in the high temperature bed is 35 mm, the diameter of the tube used in cold experiments is about 25 mm. During experiments operating parameters are variable, the bed temperature of the boiler changes from 600 to 1000°C which causes a change of about 10% of $(\rho_s C_{ps} D^{3/2} g^{1/2}/K_f)$, only one tube was used in cold experiments, so equation (5) could not be satisfied strictly all the time. These errors could be reduced by the correction

$$Nu \propto (\rho_s C_{ps} D^{3/2} g^{1/2}/K_f)^{0.23}.$$

Almost every analysis shows that Nusselt number is directly related to the 0.3 power of the Prandtl number, i.e.

$$Nu \propto Pr^{0.3}.$$

In experiments, the Prandtl number varied from 0.64 to 0.63 with the bed temperature rising from 600 to 1000°C.

3. APPARATUS AND METHOD OF MEASUREMENT

The high temperature experiments were carried out on a 0.8 t h^{-1} fluidized boiler with a section of 500 × 600 mm^2 (Fig. 2). A single tube with a diameter of 35 mm (Fig. 3(A)) was set in the bed and cooled by water from a high position vessel. The total heat transfer coefficient of the immersed tube to the bed was calculated by

$$h_t = \frac{QC_p(T_{out} - T_{in})}{F(T_b - T_w)}$$

where T_{out} and T_{in} are the outlet and inlet water temperatures, respectively.

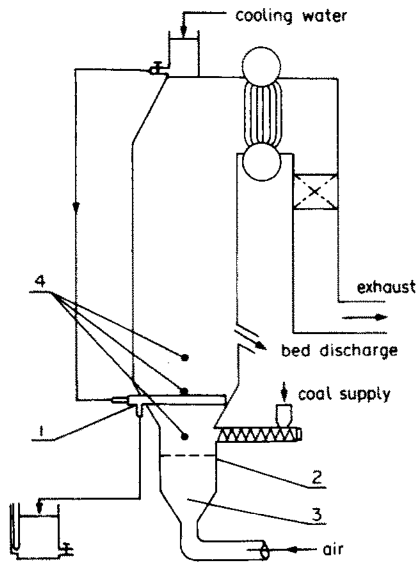

FIG. 2. The schematic diagram of fluidized bed employed for heat transfer experiments: (1) measuring tube; (2) air distributor plate; (3) air chamber; (4) thermocouple for measuring bed temperature.

Experiments at room temperature were carried out on another fluidized bed with a section of 450 × 600 mm^2, in which an electric heating tube with a diameter of 25 mm (Fig. 3(B)) was set. The total heat transfer coefficient from the bed to the tube was obtained by

$$h_c = \frac{N}{F(T_b - T_w)}$$

where N is the electric power supplied to heating the tube.

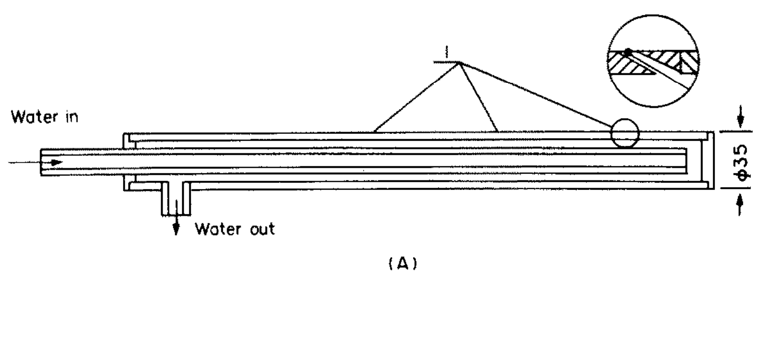

FIG. 3. The schematic diagram of measuring tubes (A, for high temperature experiments, cooled by water; B, for room temperature, heated by electricity): (1) thermocouples in contact with the tube wall; (2) heater coil.

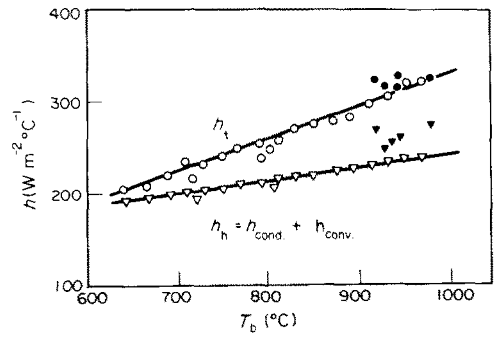

FIG. 4. Variation of h_t and h_h with bed temperature: ○, ▽, $d_s = 0.802$ mm; ●, ▼, $d_s = 0.497$ mm.

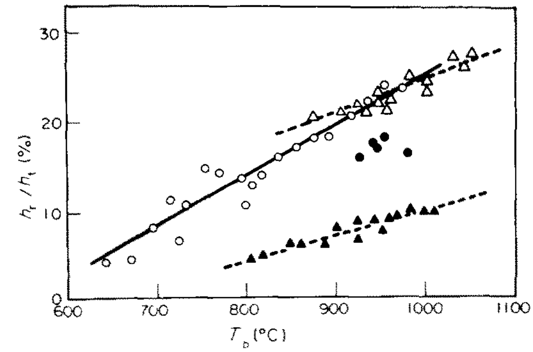

FIG. 5. Variation of radiative contribution with bed temperature and comparison with ref. [7]: ○, present $d_s = 0.802$ mm; ●, present $d_s = 0.497$ mm; △, ref. [7] $d_s = 0.755$ mm; ▲, ref. [7] $d_s = 0.234$ mm.

4. ANALYSIS OF EXPERIMENTAL RESULTS

Based on the preceding statement, a correlation between two states experiments is obtained

$$\frac{Nu_h}{Nu_c} = \frac{(\rho_s C_{ps} D^{3/2} g^{1/2}/K_f)_h^{0.23}}{(\rho_s C_{ps} D^{3/2} g^{1/2}/K_f)_c^{0.23}} \frac{Pr_h^{0.3}}{Pr_c^{0.3}}.$$

The gas heat convection and particle heat conduction at high temperature can be deduced from that at room temperature

$$h_h = \frac{K_{fh}}{K_{fc}} \frac{D_c}{D_h} \frac{Pr_h^{0.3}}{Pr_c^{0.3}} \frac{(C_{ps} D^{3/2}/K_f)_h^{0.23}}{(C_{ps} D^{3/2}/K_f)_c^{0.23}} h_c.$$

If total heat transfer coefficient at high temperature h_t is known then the radiative heat transfer coefficient is

$$h_r = h_t - h_h.$$

The results of high temperature experiments and data deduced from cold experiments are shown in Fig. 4.

This figure shows that the heat transfer coefficient increases almost linearly with bed temperature. It increases from 190 to 340 W m^{-2} °C^{-1} with a bed temperature change from 600 to 1000°C for coal $\bar{d}_s = 0.802$ mm. The increase caused by the change of thermal properties is 40 W m^{-2} °C^{-1}. The major increase is caused by radiation. Radiation exists at the bed temperature over 700°C. The radiative contribution is shown in Fig. 5. It is 3% at a bed temperature of 600°C and increases to 27% with a bed temperature of 1000°C.

Experiments were carried out with two different kinds of particles. It is generally recognized that heat transfer of smaller particles is greater than that of larger particles at room temperature. The experimental results show that the total heat transfer coefficient is almost the same for two kinds of particles at high temperature. The explanation of this result is that the radiation of larger particles is greater than that of smaller particles, because larger particles have a greater thermal capacity, hence their temperature drop in a gas boundary layer during contact with the tube is slow. Due to the heat radiation of particles has a direct relation with the fourth power of their temperature, the radiation contribution increases with

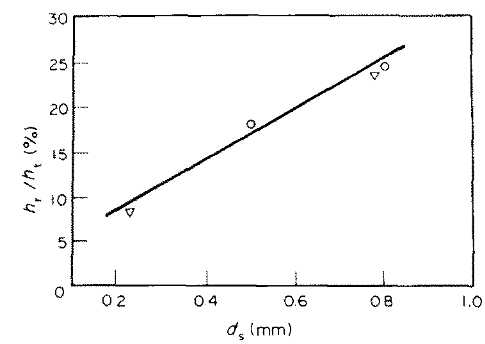

FIG. 6. Variation of radiative contribution with particle diameter d_s at a bed temperature of 950°C: ○, present; ▽, ref. [7].

average diameter of particles rapidly. It is 24% for particles with $d_s = 0.802$ at a bed temperature of 950°C, but decreases to 17% for particles with $d_s = 0.197$ mm.

Results of the present experiments are compared with those of ref. [7] and the variation of the radiative contribution with the average diameter of particles is shown in Fig. 6.

5. CONCLUSIONS

(1) The experimental results and their comparison with other papers show that indirect measurement of the radiative heat transfer coefficient is suitable and reliable.

(2) The radiative contribution rapidly increases with bed temperature and particle diameter as follows:

	$T_b = 600$°C	$T_b = 950$°C	$T_b = 1000$°C
$d_s = 0.802$ mm	3%	24%	27%
$d_s = 0.497$ mm	—	17%	—

(3) The radiative heat transfer is obvious when the bed temperature is higher than 800°C, and increases

almost linearly with the temperature of the fluidized bed.

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RECHERCHE EXPERIMENTALE SUR LE TRANSFERT RADIATIF DE CHALEUR DANS LES LITS FLUIDISES

Résumé—On présente une nouvelle méthode pour mesurer le transfert radiatif de chaleur dans les lits fluidisés. Des expériences sont faites sur une chaudière à combustion en lit fluidisé de 0,8 t h^{-1}. Les cendres sont traitées dans un lit fluidisé à la température ambiante. Tandis que le transfert radiatif à température ambiante est insignifiant, sa contribution à haute température peut être obtenue par la comparaison des résultats expérimentaux à haute et faible températures. A partir de l'étude expérimentale, une contribution radiative est donnée en fonction de la température du lit et de la taille des particules. Les résultats sont comparés avec ceux d'autres références.

EXPERIMENTELLE UNTERSUCHUNG DES STRAHLUNGSAUSTAUSCHES IM WIRBELBETT

Zusammenfassung—Es wird eine neue Methode zur Bestimmung des Strahlungsaustausches im Wirbelbett vorgestellt. Die Experimente werden an einem mit 0.8 t h^{-1} fluidisierten Bett der Brennkammer eines Dampfkessels durchgeführt. Die Verbrennungsrückstände der Kohle werden in ein Wirbelbett bei Raumtemperatur eingebracht. Da der Strahlungsaustausch bei Raumtemperatur unbedeutend ist, kann der Anteil bei hoher Temperatur durch Vergleich experimentell ermittelter Daten bei hohen und niederen Temperaturen ermittelt werden. Durch experimentelle Untersuchungen wurde der Strahlungsanteil als Funktion der Bett-Temperatur und der Partikelgröße bestimmt. Die Ergebnisse werden mit Literaturangaben verglichen.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ РАДИАЦИОННОГО ТЕПЛОПЕРЕНОСА В ПСЕВДООЖИЖЕННЫХ СЛОЯХ

Аннотация—Предложен новый метод измерения радиационного теплопереноса в псевдоожиженных слоях. Эксперименты проводились в топке котла производительностью 0,8 т/ч для сжигания в псевдоожиженном слое. Оставшийся после сжигания угля шлак использовался в псевдоожиженном слое при комнатной температуре. Поскольку радиационный теплоперенос при комнатной температуре незначителен, его вклад при высоких температурах может быть определен сравнением результатов экспериментов при малых и больших температурах. При экспериментальном исследовании вклад радиации определялся как функция температуры слоя и размера частиц. Полученные результаты были сравнены с данными других авторов.