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Combined Radiation-Convection Heat Transfer Analysis in a Circulating Fluidized Bed Boiler

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Abstract

A computer program is developed to analyze two-dimensional combined radiation-convection heat transfer in a circulating fluidized bed boiler (CFBB). The radiative heat transfer in the dispersed system is analyzed by a revised Monte Carlo method, which can accurately predict radiative heat transfer in the CFBB, together with results of convective heat transfer among the gas, the particles and the furnace walls. The convective heat transfer between the particles and the furnace walls are calculated by Martin's model. The temperatures of gas and particles together with wall heat flux distribution are obtained. Theoretical results agree well with the experimental data obtained from Studsvik 2.5MW CFBB.

1. Introduction

Recently, considerable attention has been focused on the circulating fluidized bed boiler (CFBB) because of its high combustion efficiency and low air pollution. To apply this technology to industry, it is necessary to analyze heat transfer in detail for comparing with experimental results.

There are numerous research results of convective heat transfer in CFBB (for example, 1-7). However, not adequate are the results of radiative heat transfer which is very important in high temperature cases.

In this paper, radiative heat transfer is analyzed by a revised Monte Carlo method[8], which can accurately predict radiative heat transfer in furnaces. Together with results of convective heat transfer calculated by Martin's model[1, 2]. The temperatures of gas and particles together with wall heat flux distribution are obtained. Theoretical results are compared with Johnsson[7]'s experimental data.

2. Theoretical model

The model considers (i) radiation from heat generating coal particles in combustion, non-heat generating particles of bed materials, gas and enclosure wall, (ii) absorption of radiation (i), (iii) anisotropic scattering by particles, (iv) heat released by heat generating

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particles, (v) convective heat transfer between gas and particles and (vi) convective heat transfer from the bed to the wall. Combined radiation-convection heat transfer in a two-dimensional rectangular (0.7m×7.0m) duct shown in Fig. 1 is analyzed. This model's target is above the secondary air inlet at Studsvik 2.5MW CFBB(5)-(7). The temperature and emissivity of wall are 600K and 0.95(7), respectively. It is assumed that the gas with suspending particles at 1000K flows upward from the lower wall. The properties of gas are shown in Table 1. The vertical bulk density takes the values listed in Table 2, referring to Johnsson(7)'s experimental data presented in Fig. 2. Particle 1 refers to heat generating particles, while particle 2 represents non-heat generating particles. The size and properties are given in Table 3. The bulk density ratio of particles 1 and 2 is 1 to 49 as determined by the experimental data(9). The gas velocity in uniform upflows is at 4.8m/s and the mass flux of particle is $12 kg/m^2/s$(10). The upper and lower walls are porous and black at 1000K and 600K respectively.

The radiative characteristics of the gas with particles can be determined by the shape, size, optical characteristics (emissivity) of particles, particle number density (N_{s1}, N_{s2}), and the thermal radiative characteristics of gas. Let β be the extinction coefficient, consisting of the absorption coefficients of the gas and particles and the scattering coefficient. Let ω be the scattering albedo. Then, one has

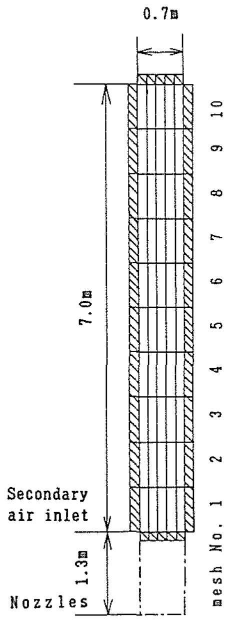

Fig. 1 Theoretical model

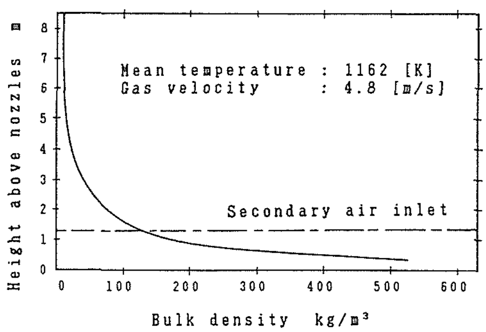

Fig. 2 Experimental results of vertical bulk density

Table 1 Some properties of gas

Absorption coef.	[m^{-1}]	a_g = 0.2[18]
Density	[kg/m^3]	ρ_g = 0.32[17]
Specific heat	[J/kg/K]	c_{pg} = 1160[17]
Thermal conductivity	[W/m/K]	λ_g = 0.0717[17]
Prandtl number	[—]	Pr = 0.742[17]
Kinematic viscosity coef.	[m^2/s]	ν = 1.43×10^{-4}[17]

Table 2 Bulk Density [kg/m^3]

mesh	Particle 1	Particle 2	Total
10	0.2	9.8	10.0
9	0.24	11.76	12.0
8	0.3	14.7	15.0
7	0.34	16.66	17.0
6	0.4	19.6	20.0
5	0.5	24.5	25.0
4	0.6	29.4	30.0
3	0.8	39.2	40.0
2	1.2	58.8	60.0
1	1.8	88.2	90.0

Table 3 Size and some properties of particles

		Particle 1	Particle 2
Diameter	[μm]	d_{s1} = 240[7]	d_{s2} = 240[7]
Emissivity	[—]	ε_{s1} = 0.85[15]	ε_{s2} = 0.6[7]
Density	[kg/m^3]	ρ_{s1} = 1300[16]	ρ_{s2} = 3000[7]
Specific heat	[J/kg/K]	c_{ps1} = 1000[16]	c_{ps2} = 1300[16]

$$\beta = a_g \psi + a_{s1} + a_{s2} + \sigma_{s1} + \sigma_{s2} \tag{1}$$

$$\omega = (\sigma_{s1} + \sigma_{s2}) / \beta \tag{2}$$

where

ψ (*void fraction*)

$= \{$*volume of gas*/(*volume of gas and particles*)$\}$

$1 - \psi = \{$*volume of particles*/(*volume of gas and particles*)$\}$

$$= \frac{4}{3}\pi (d_{s1}/2)^3 N_{s1} + \frac{4}{3}\pi (d_{s2}/2)^3 N_{s2} \tag{3}$$

$$a_{s1} = \varepsilon_{s1} \pi (d_{s1}/2)^2 N_{s1} \tag{4}$$

$$a_{s2} = \varepsilon_{s2} \pi (d_{s2}/2)^2 N_{s2} \tag{5}$$

$$\sigma_{s1} = (1 - \varepsilon_{s1}) \pi (d_{s1}/2)^2 N_{s1} \tag{6}$$

$$\sigma_{s2} = (1 - \varepsilon_{s2}) \pi (d_{s2}/2)^2 N_{s2} \tag{7}$$

a and σ are the absorption and scattering, respectively. The subscripts s1, s2 and g denote particles 1, 2 and gas respectively. Such particles have anisotropic phase function[11]

$$\phi(\eta) = 8/(3\pi)(\sin\eta - \eta\cos\eta) \tag{8}$$

which determines the direction of scattered energy. It is valid for a sphere with diffuse surface and strong backward scattering characteristics. The absorption and scattering of radiative energy by the particles are treated them optically, since the particle size ($240\mu m$) is over twenty times the wave length range (under $10\mu m$) of radiation by black body at 1000-1200K.

Energy equations for the gas, particles and wall elements are

[gas] $$Q_{r,\,out,\,g}+Q_{cgw}+Q_{cgs1}+Q_{cgs2}+Q_{f,\,out,\,g}=Q_{r,\,in,\,g}+Q_{f,\,in,\,g} \quad (9)$$

[particle 1] $$Q_{r,\,out,\,s1}+Q_{cs1w}+Q_{f,\,out,\,s1}=Q_{r,\,in,\,s1}+Q_{cgs1}+Q_{hs1}+Q_{f,\,in,\,s1} \quad (10)$$

[particle 2] $$Q_{r,\,out,\,s2}+Q_{cs2w}+Q_{f,\,out,\,s2}=Q_{r,\,in,\,s2}+Q_{cgs2}+Q_{f,\,in,\,s2} \quad (11)$$

[wall] $$Q_{r,\,out,\,w}+Q_a=Q_{r,\,in,\,w}+Q_{cgw}+Q_{cs1w}+Q_{cs2w} \quad (12)$$

These equations are solved by a Newton-Raphson method numerically, for the temperatures of the gas and particles as well as wall heat flux distribution. Here, $Q_{r,\,out}$ is the total radiative energy emitted from an element and absorbed by other elements.

[gas] $$Q_{r,\,out,\,g}=4\sigma a_g\psi T_g^4\Delta V \quad (13)$$

[particle 1] $$Q_{r,\,out,\,s1}=4\sigma a_{s1}T_{s1}^4\Delta V \quad (14)$$

[particle 2] $$Q_{r,\,out,\,s2}=4\sigma a_{s2}T_{s2}^4\Delta V \quad (15)$$

[wall] $$Q_{r,\,out,\,w}=\varepsilon_w\sigma T_w^4\Delta S \quad (16)$$

where ΔV is element volume of gas; ΔS, element area of wall; σ, Stefan-Boltzmann constant; Q_a, heat load on wall; Q_f, enthalpy transport; Q_{cgw}, Q_{cs1w}, Q_{cs2w}, convective heat transfer between the wall and the gas, between the wall and particle 1, between the wall and particle 2 respectively; and Q_{cgs1}, Q_{cgs2}, convective heat transfer between the gas and particle 1 and 2 respectively. Q_{hs1} is the heat generation rate by particle 1, assumed to be proportional to the bulk density. The total heat generation is 2.5MW. Q_{rin} can be obtained by adding all energy components transferred from all other gas and wall elements by means of the READ (Radiative Energy Absorption Distribution)(8). The READ is defined as the ratio of the energy emitted from an element and absorbed by another element calculated by a Monte Carlo method.

The Martin's model(1, 2) is employed to determine the particle convective heat transfer as follows: A Nusselt number for this heat transfer coefficient is expressed as Eq. (17). The value of C in Eq. (18) is related to the thermal boundary layer thickness ($2<C<4$), and is found to be 2.6 by experiments(2, 5). The value of ψ_L in Eq. (19), void fraction at particle minimum fluidization velocity, is assumed to be 0.46(4). The first term in Eq. (20) denotes thermal resistance by the gas, and can be calculated from Schlunder(12)'s formula (Eq. (21)). Kn, Knudsen number, is expressed as $2l/d_s$ (l is a modified mean free path of the gas molecules) and can be calculated from the kinetic theory (Eq. (22)). The value of γ in Eq. (22) is the particle accommodation coefficient at temperature ($0<\gamma<1$) and signifies the incompleteness of heat exchange between the wall and the particles. It can be calculated using Martin[1]'s equation (23). The second term in Eq. (20) expresses thermal resistance in the solid particle. It may be neglected since it is usually very small compared with the first term.

$$Nu_s = (1-\psi) Z (1 - exp(-N)) \tag{17}$$

$$N = Nu_{ws} / CZ \tag{18}$$

$$Z = \frac{\rho_s c_{ps}}{6\lambda_g} \left\{ \frac{g d_s^3 (\psi - \psi_L)}{5(1-\psi_L)(1-\psi)} \right\}^{1/2} \tag{19}$$

$$\frac{1}{Nu_{ws}} = \frac{1}{Nu_{ws(max)}} + \frac{\lambda_g / \lambda_s}{Nu_{is}} \tag{20}$$

$$Nu_{ws(max)} = 4\{(1+Kn) \ln (1 + \frac{1}{Kn}) - 1\} \tag{21}$$

$$Kn = \frac{4}{d_s} \left(\frac{2}{\gamma} - 1 \right) \frac{\lambda_g (2\pi RT/M)^{1/2}}{P(2C_{pg} - R/M)} \tag{22}$$

$$\gamma = (1 + 10^{\{(0.6B-1-1000/T)/B\}})^{-1}, \ B = 2.8 \tag{23}$$

The convective heat transfer coefficient between the wall and the gas is calculated by the equations[13] of heat transfer between the plate and laminer flow:

$$Nu_x = 0.332 Re_x^{1/2} Pr^{1/3} \qquad (0.6 < Pr) \tag{24}$$

Convective heat transfer between the gas and the particles is calculated by the equations[14] for the forced convective heat transfer using the velocity difference between the gas and the particles:

$$Nu_{gs} = 2.0 + 0.6 Re_{gs}^{1/2} Pr^{1/3} \qquad (0.6 < Pr < 380) \tag{25}$$

valid for $1 < Re_{gs} < 10^5$. In the present case, $Re_{gs} = 6.7 \sim 8.2$.

3. Theoretical results

Theoretical results of temperature distribution of the gas and particles are shown in Fig. 3. The gas and particle temperatures are in the range of 1000-1200K. This coincides with Johnsson[7]'s experimental mean temperature (1162K) in the furnace. The gas temperature is almost equal to that of the non-heat generating particles, while the temperature of heat generating particles is about 30 degrees higher.

The results for wall heat flux are shown in Fig. 4. In the lower part of the bed with high bulk density, the radiative heat flux is in the same order of magnitude as the convective heat flux. But in the upper part, the radiative heat flux dominates.

Comparison between theoretical and experimental results[7] for the wall heat transfer coefficient agrees well as demonstrated in Fig. 5.

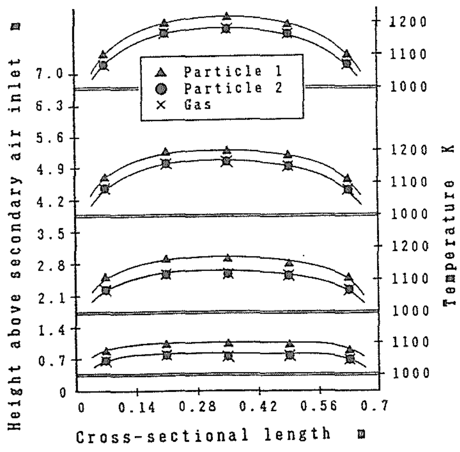

Fig. 3 Theoretical results of temperature distribution

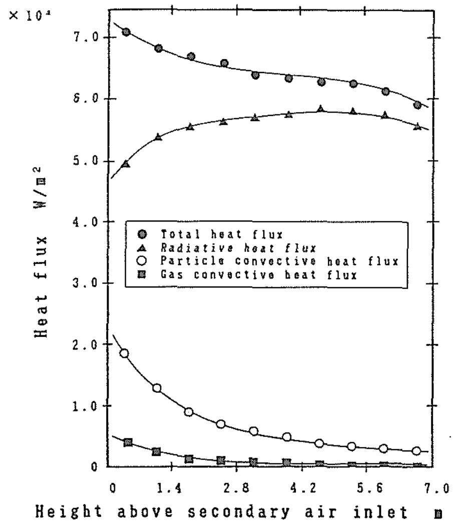

Fig. 4 Theoretical results of wall heat flux

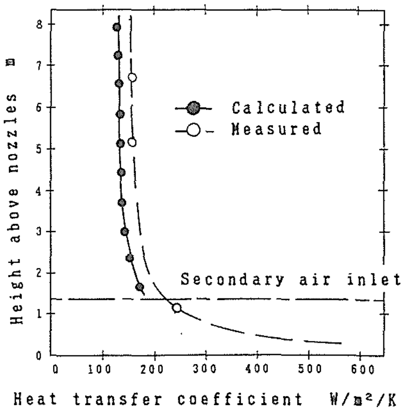

Fig. 5 Theoretical and experimental results of wall-gas heat transfer coefficirent

4. Conclusions

1. Two-dimensional combined radiation-convection heat transfer is analyzed using a Monte Carlo method. It is disclosed that the theoretical results agree well with the experimental results.
2. In the lower part of the bed with high bulk density, the radiative heat transfer to the wall is in the same order of magnitude as the convective heat transfer. However, in the upper part, the radiative heat transfer mechanism dominates.
3. The gas temperature is almost equal to that of the non-heat generating particles, while the temperature heat generating particles is about 30 degrees higher.
4. Theoretical results of the vertical mean temperature of the gas and particles reach 1100K. But the temperature difference between the bed center and the wall is 100K in the absence of horizontal heat mixturing.

References

1) Martin, H., Chem. Ing. Tech., 52(1980), 199-209
2) Martin, H., Chem. Eng. Prog., 18(1984), 157-223
3) Grace, J. R., CFB. Tech, P. Basu, ed., Pergamon, Toronto, (1986), 63-80
4) Wu, R. L., Grace, J. R., et. al., A. I. Ch. E. Journal, 35-10(1989), 1685-1691
5) Johnsson, F., Andersson, B-Å, et. al., Paper at IEA meeting on Mathematical Modelling, Boston, May (1987)
6) Andersson, B-Å., Johnsson, F, et. al., 9th Int. Conf. on FBC, Boston, May (1987)
7) Johnsson, F., The Degree of Licentiate of Eng., Göteborg (1987)
8) Taniguchi, H., et. al., Int. J. for Num. Methods in Eng., 25-2 (1988), 581-592.
9) Stromberg, L., 7th Int. Conf. on FBC, Philadelphia, October (1982)
10) Kobro, H., et. al., Proc. 1st Intl Conf. on CFBB, (1985), 263-272
11) Siegel, R., et. al., Thermal Radiation Heat Transfer 2nd Ed., McGraw-Hill, (1981), 581
12) Schlünder, E. U., Chem. Ing. Tech., 43 (1971), 651-654
13) Eckert, E. R. G., et. al., R. M. McGraw-Hill, (1972)
14) Ranz, W. E., et. al., Chem. Eng. Prog., 48 (1952), 141-173
15) Ross, I. B., et. al., Trans. Inst. Chem. Eng., 59 (1981)
16) JSME Data Book : Heat Transfer (4th Edition), 321
17) JSME Data Book : Heat Transfer (4th Edition), 329
18) Hottel, H. C., et. al., Radiative Transfer, McGraw-Hill, (1967)