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HEAT TRANSFER BETWEEN A CIRCULATING FLUIDIZED BED AND EXTENDED SURFACES: ACCOUNT FOR PRESSURE AND TEMPERATURE EFFECTS

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A phenomenological model of heat transfer in the transport zone of a circulating fluidized bed (CFB) is developed; the model allows for basic specific features of the process: a gas gap at the riser wall, the temperature profile in a horizontal cross section of the riser, and the dependence of their characteristics on the concentration of the particles. On the basis of model concepts test data are generalized in the form of simple semi-empirical relations for calculating the conductive-convective component of the coefficient of heat transfer and the total coefficient of heat transfer between extended surfaces ($L \geq 0.5$ m) and the CFB in the transport zone. These formulas allow for the effect of pressure and temperature and are verified within a rather wide range of variation of the experimental conditions.

A knowledge of the laws governing heat transfer of extended surfaces ($L \geq 0.5$ m) in the transport zone of a CFB under conditions of elevated temperatures and pressures is important for designing boilers and gas generators with a CFB in which water-cooled surfaces of a riser play the role of a heat exchanger and, as a rule, are rather long.

The literature presents the following semi-empirical relations for calculation of $\alpha_{\text{c-c}}$ and α under the above-stated conditions [1]:

$$\text{Nu}_{\text{c-c}} = 2.85 \left(\frac{\Delta p}{(\rho_s - \rho_f)(1 - \varepsilon_{mf})\, g\Delta L}\right)^{0.5} + 3.28 \cdot 10^{-3}\, \text{Re}_w \,\text{Pr}\,, \tag{1}$$

$$\text{Nu} = \sqrt{\text{Nu}^2_{\text{c-c}} + \text{Nu}^2_{\text{rad}}}\,, \tag{2}$$

$$\text{Nu}_{\text{rad}} = \frac{d}{\lambda_f}\, \varepsilon_{\text{rad}} \sigma_0 \frac{T^4_\infty - T^4_w}{T_\infty - T_w}\,, \tag{3}$$

$\text{Re}_w = \varphi(\text{Re}_{mf}, \text{Re}_t, \Delta p/((\rho_s - \rho_f)(1 - \varepsilon_{mf}) g\Delta L)$, and ε_{rad} is taken to be equal to 0.91.

As is shown by an analysis, formulas (1)-(3) have two substantial drawbacks. The form of the conductive component in (1) assumes a rather sharp dependence of it on the diameter of the particles ($\alpha_{\text{cond}} \sim d^{-1}$), which contradicts test data (see, e.g., [2]). In the expression for α_{rad} the presence of a temperature profile in a horizontal cross section of the riser is disregarded, which should lead to the appearance of the value of the particle temperature T_s at the riser wall instead of T_∞ in (3). T_s differs greatly from T_∞. These two facts impose certain limitations on the possibility of using formulas (1)-(3) and necessitate obtaining relations devoid of the drawbacks mentioned.

We posed the problem: to construct a simple and rather adequate model of the phenomenon with a minimum number of easily determined empirical parameters on the basis of modern concepts of the laws governing heat transfer in a CFB and thus to develop a technique for calculating $\alpha_{\text{c-c}}$ and α for the CFB transport zone.

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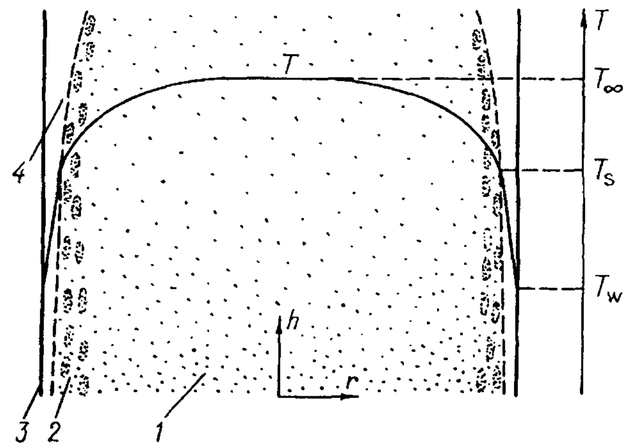


Fig. 1. Structure of a circulating fluidized bed and temperature profile (T) in the transport zone of a riser: 1) central zone of an ascending flow of particles, 2) annular zone of a predominantly descending flow of particles, 3) riser wall, 4) gas film.

Conductive-Convective Heat Transfer. The physical model adopted in the present paper resembles in many respects a two-zone film model of heat transfer in a bubble fluidized bed that was suggested earlier in [3] and assumes (Fig. 1):

a) the presence of a gas film of variable thickness between the riser surface and the annular bed of descending particles;

b) the existence of a temperature profile in a horizontal cross section of the riser and a difference between the bed core temperature (T_∞) and the temperature of the first (from the heat transfer surface) row of particles (T_s);

c) a linear profile of the temperature in the gas film, in which the temperature varies from T_w to T_s;

d) a nonlinear dependence of the gas film thickness on the diameter and concentration of the particles at the wall:

$$\delta_f/d = k_1 \mathrm{Ar}^{-k_2} (\rho_w/\rho_s)^{-k_3} ; \tag{4}$$

e) an effective thermal conductivity of the gas film that consists of conductive and convective components:

$$\lambda_{ef} = \lambda_f + k_4 \rho_f c_f u_t d \, (\rho_w/\rho_s)^{-k_5} . \tag{5}$$

The form of λ_{ef} allows for the effect of particle motion at the riser wall on enhancement of horizontal heat transfer in the gas. Here the actual floating velocity of a single particle for the conditions of particle motion in the transport zone of the CFB is taken as the velocity scale. It is easily seen that the second term in (5) describing the contribution of gas convection can be substantial at elevated pressures.

We write the heat-balance equation that determines $\alpha_{c\text{-}c}$:

$$\alpha_{c-c} (T_\infty - T_w) = - \lambda_{ef} (\partial T/\partial r)_{r=D/2} . \tag{6}$$

Using assumption c), we can write for the temperature gradient

$$(\partial T/\partial r)_{r=D/2} = (T_w - T_s)/\delta_f . \tag{7}$$

Substituting $(\partial T/\partial r)_{r=D/2}$ in (6), we obtain

$$\alpha_{c-c} = \frac{\lambda_{ef}}{\delta_f} \frac{T_s - T_w}{T_\infty - T_w} = \frac{\lambda_{ef}}{\delta_f} \Theta_s . \tag{8}$$

The dimensionless relative temperature of the first row of particles is a characterististic of the temperature profile in a horizontal cross section of the riser, and within the framework of the model, it plays the role of an empirical parameter that substantially simplifies the expression for $\alpha_{c\text{-}c}$. In [4] the results of an experimental study of the temperature distribution in different horizontal cross sections of the riser of a boiler with a CFB with a power of 12 MW is presented. We generalized these data in the following compact form:

$$\Theta_s = 0.8\ \mathrm{Fr}_t^{0.08}\ (h/H)^{-0.20}\ . \tag{9}$$

For the operating conditions of this boiler a formula was suggested in [5] for calculation of the mean concentration of the particles in a horizontal cross section of the riser (the transport zone)

$$\rho/\rho_s = 0.053\ \mathrm{Fr}_t^{0.62}\ (h/H)^{-0.45}\ . \tag{10}$$

Combining (9) and (10) gives the following dependence of Θ_s on ρ/ρ_s:

$$\Theta_s = 1.17\ (\rho/\rho_s)^{0.13}\ (h/H)^{-0.14}\ . \tag{11}$$

Allowing for the fact that in the transport zone of a CFB $h/H \simeq 0.3-1.0$ we obtain an estimate: $(h/H)^{-0.14} = 1-1.18$. This makes it possible to present Θ_s, with an error of no more than 10%, in the form

$$\Theta_s \simeq 1.29\ (\rho/\rho_s)^{0.13} = k_6\ (\rho_w/\rho_s)^{0.13}\ , \tag{12}$$

assuming $\rho_w \sim \rho$. Substituting in (8) the expressions for the quantities in it from (4), (5), and (12), we have

$$\alpha_{c-c} = \frac{k_6}{k_1}\frac{\lambda_f}{d}\,\mathrm{Ar}^{k_2}\left(\frac{\rho_w}{\rho_s}\right)^{k_3+0.13} + \frac{k_4 k_6}{k_1}\,c_f\rho_f u_t\,\mathrm{Ar}^{k_2}\left(\frac{\rho_w}{\rho_s}\right)^{k_3-k_5+0.13}\ . \tag{13}$$

In dimensionless form, (13) is

$$\mathrm{Nu}_{c-c} = \frac{k_6}{k_1}\,\mathrm{Ar}^{k_2}\left(\frac{\rho_w}{\rho_s}\right)^{k_3+0.13} + \frac{k_4 k_6}{k_1}\,\mathrm{Re}_t\,\mathrm{Pr}\,\mathrm{Ar}^{k_2}\left(\frac{\rho_w}{\rho_s}\right)^{k_3-k_5+0.13} \tag{14}$$

The second term in (14) is the convective component of $\alpha_{c\text{-}c}$ and makes a considerable contribution at large Re_t and Ar. Under these conditions we have from the familiar Todes formula [6]

$$\mathrm{Re}_t = \mathrm{Ar}/(18 + 0.61\sqrt{\mathrm{Ar}}) \simeq 1.64\sqrt{\mathrm{Ar}}\ . \tag{15}$$

With account for (15), the final form of the model relation determining $\mathrm{Nu}_{c\text{-}c}$ is the following:

$$\mathrm{Nu}_{c-c} = \frac{k_6}{k_1}\,\mathrm{Ar}^{k_2}\left(\frac{\rho_w}{\rho_s}\right)^{k_3+0.13} + 1.64\,\frac{k_4 k_6}{k_1}\,\mathrm{Ar}^{k_2+0.5}\left(\frac{\rho_w}{\rho_s}\right)^{k_3-k_5+0.13}\mathrm{Pr}\ . \tag{16}$$

To find the dimensionless coefficients k_1, k_2, ..., k_5,*) which determine the parameters of the model δ_f and λ_{ef}, test data given in the literature (see Table 1) were processed in accordance with (16). The data were processed in the ordinary way in two stages. First, data of [7-9] were generalized for α_{cond}, and the coefficients k_1, k_2, and k_3 were found. Then results of [1] obtained at elevated pressures were generalized and the remaining coefficients k_4 and k_5 were determined (see Table 2). As a result the model equation (16) turned into the following semi-empirical correlation for calculation of $\alpha_{c\text{-}c}$:

*) The coefficient k_6 is determined directly from the ratio of ρ and ρ_w : $\rho_w/\rho \simeq 2.75$ [7], and therefore, it follows from (12) that $k_6 = 1.29/1.14 = 1.13$.

TABLE 1. Conditions of Experiments on Measuring $\alpha_{c\text{-}c}$, α

Reference	d, mm	t_∞, °C	L, m	p, MPa	Disperse material
[1]	0.0585	20		0.1–5.0	Glass beads
	0.194	20		0.1–5.0	Same
			0.5		
	0165	20		0.5–5.0	Quartz sand
	0.0637	20		0.1–5.0	Bronze beads
	0.827	20		0.1–5.0	Polysterene
[7]	0.040	20	0.7		Glass beads
	0.130	20		0.1	Same
	0.300	20			Same
[8]	0.300	230	0.7	0.1	Sand
[9]	0.095	400	0.95	0.1	Same
[11]	0.241; 0.299	347–880	1.22	0.1	Same
	0.241; 0.222	410–870	1.59	0.1	Same

TABLE 2. Values of the Coefficients k_i in (4) and (5)

k_1	k_2	k_3	k_4	k_5
1.13	0.19	0.37	0.0003	0.50

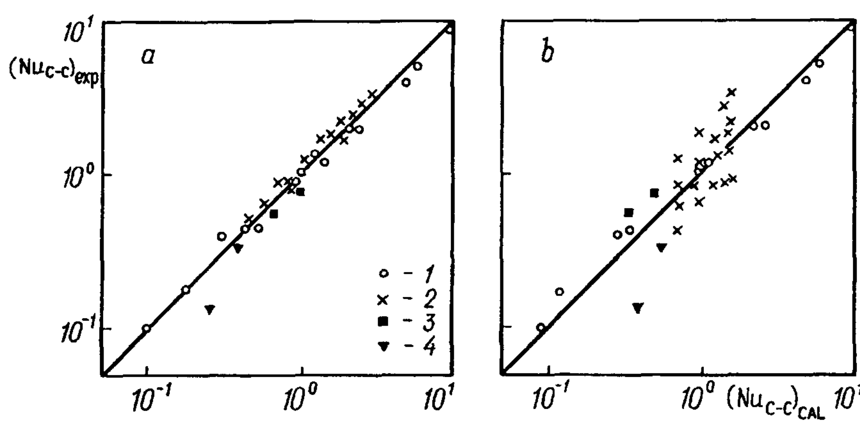


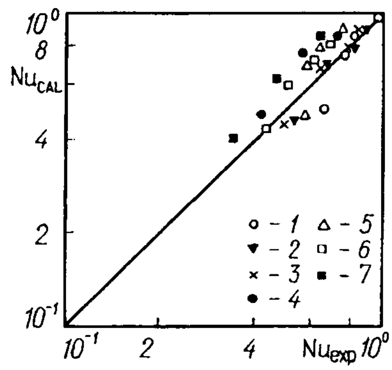
Fig. 2. Comparison of experimental data and data calculated by Eq. (18) (a) and by Eq. (1) (b): 1) [1], 2) [7], 3) [8], 4) [9].

$$\mathrm{Nu}_{c-c} = 1.0\,\mathrm{Ar}^{0.19}\left(\frac{\rho_w}{\rho_s}\right)^{0.5} + 0.00049\,\mathrm{Ar}^{0.69}\,\mathrm{Pr}\,. \tag{17}$$

With allowance for $\rho_w \simeq 2.75\rho$, (17) can be rewritten in a more convenient form:

$$\mathrm{Nu}_{c-c} = 1.65\,\mathrm{Ar}^{0.19}\left(\frac{\rho}{\rho_s}\right)^{0.5} + 0.00049\,\mathrm{Ar}^{0.69}\,\mathrm{Pr}\,. \tag{18}$$

Figure 2a shows a comparison of data calculated by (18) and data obtained experimentally [1, 7-9]. The root-mean-square deviation between them is 10%. A comparison of these test data with a calculation by Eq. (1) (Fig. 2b) showed a discrepancy of 21%, which is associated with the incorrect dependence of the conductive component in (1) on the diameter of the particles noted above. The obtained semi-empirical relation (18) was



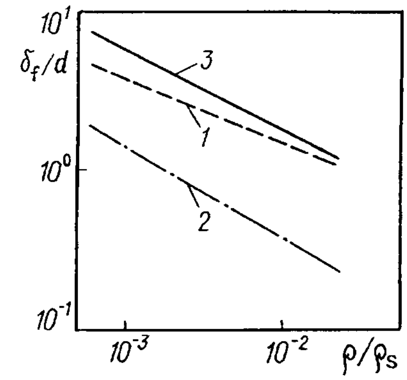


Fig. 3. Comparison of experimental data [11] and data calculated by Eq. (20): 1) $t_\infty = 880^\circ$C, 2) 701, 3) 587, 4) 347 (vertical tube); 5) 870, 6) 681, 7) 410 (membrane wall). $\varepsilon_s = \varepsilon_w = 0.8$; $t_w = 150^\circ$C.

Fig. 4. Gas-film thickness: 1) calculation by (21), 2) (22), 3) (23).

verified in the following range of variation of the test conditions: $0.1 \le p \le 5.0$ MPa, $0.058 \le d \le 0.827$ mm, $0.5 \le L \le 0.95$ m, $\rho/\rho_s \le 6\cdot10^{-2}$ and can be used for calculating $\alpha_{c\text{-}c}$.

Complex Heat Transfer. At elevated temperatures Eq. (18) should be supplemented by the expression for radiative heat transfer

$$\alpha_{rad} = \frac{\sigma_0 (T_s^2 + T_w^2)(T_s + T_w)}{1/\varepsilon_{ef} + 1/\varepsilon_w - 1}, \tag{19}$$

where in accordance with (12)

$$T_s = T_w + 1.29\,(\rho/\rho_s)^{0.13}\,(T_\infty - T_w), \tag{19a}$$

and the effective emissivity of the CFB $\varepsilon_{ef} = \varepsilon_s^{0.31}$ [10]. The formula for the coefficient of complex heat transfer takes the form

$$\mathrm{Nu} = 1.65\,\mathrm{Ar}^{0.19}\left(\frac{\rho}{\rho_s}\right)^{0.5} + 0.00049\,\mathrm{Ar}^{0.69}\,\mathrm{Pr} + \frac{\sigma_0 d}{\lambda_f}\,\frac{(T_s^2 + T_w^2)(T_s + T_w)}{1/\varepsilon_{ef} + 1/\varepsilon_w - 1}. \tag{19}$$

A traditional problem that arises in using relations of the type (20), is the choice of the determining temperature $\langle T\rangle$ in calculations of the gas parameters ρ_f, ν_f, and λ_f. It is impossible to give definite recommendations on $\langle T\rangle$ within the framework of the present model. Therefore, it is expedient to use a result we obtained in [2] for a fluidized bed: $\langle T\rangle = (T_s + T_w)/2$.

Figure 3 presents results of a comparison of test data of [11] (see Table 1) with data calculated by (20). The root-mean-square deviation of the experimental points from the calculated points is 18%. The range for verification of (20) is: $0.1 \le p \le 5.0$ MPa; $0.058 \le d \le 0.827$ mm; $0.5 \le L \le 1.59$ m; $\rho/\rho_s \le 6\cdot10^{-2}$; $293 \le T_\infty \le 1153$ K.

It is of undoubtedly of interest to compare thicknesses of a gas film at a heat-transfer surface calculated using (4) and Table 2 with direct measurements of δ_f [12] and with values of δ_f obtained on the basis of recalculation of values of the coefficient of heat transfer of small detectors (the coefficient of local heat transfer) [2]. From (4) with allowance for the values of the coefficients k_1, k_2, and k_3 we have an expression for δ_f:

$$\delta_f/d = 0.78\,\mathrm{Ar}^{-0.19}\,(\rho/\rho_s)^{-0.37}. \tag{21}$$

In Fig. 4 a calculation by (21) is compared to the formula [12]

$$\delta_f/d = 0.0287\,(\rho/\rho_s)^{-0.581}, \tag{22}$$

obtained on the basis of generalization of results of direct measurements in a CFB of diameter 0.2 m (d = 0.182 mm). The same figure presents a calculation by the formula [2]

$$\delta_f/d = 0.81\ \mathrm{Ar}^{-0.23}\,(\rho/\rho_s)^{-0.5}\,, \tag{23}$$

found on the basis of recalculation of test data on local heat transfer. The values of Ar in (21) and (23) were determined for the conditions of the experiments [12]. As is seen from Fig. 4, satisfactory qualitative agreement is observed between results of a calculation by (21) and by (23) and the experimental relation (22).

Conclusions. A simple model of heat transfer in the transport zone of a CFB is suggested that allows for the effect of a gas film at the heat-transfer surface. Use of experimentally determined values of the temperature of the particles of the first row made it possible to reduce to a minimum the number of model parameters (formula (8)). The semi-empirical relations (18) and (20) found for calculation of the heat-transfer coefficients $\alpha_{c\text{-}c}$ and α are verified within a wide range of variation of the test conditions and may be recommended for engineering practice.

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NOTATION

$\mathrm{Ar} = gd^3(\rho_s/\rho_f - 1)/\nu_f^2$, Archimedes number; cf, specific heat of the gas; d, particle diameter; $\mathrm{Fr_f} = (u - u_t)^2/gH$, modernized Froude number; g, acceleration of gravity; h, height above the gas-distributor grid; H, riser height; k_i, dimensionless coefficients; L, length of the heat-transfer surface; $\mathrm{Nu} = \alpha d/\lambda_f$, Nusselt number; $\mathrm{Pr} = c_f\rho_f\nu_f/\lambda_f$, Prandtl number; $\mathrm{Re_t} = u_t d/\nu_f$, $\mathrm{Re}_{mf} = u_{mf}d/\nu_f$, Reynolds numbers; r, radial coordinate; t, T, temperature; T_s, temperature of the particles of the first row (from the heat transfer surface); u_{mf}, u_t, velocity of the onset of fluidization and floating, respectively; α, coefficient of heat transfer; δ_f, gas-film thickness; ε_s, ε_w, emissivity of the particles and of the heat-transfer surface, respectively; $\Theta = (T - T_w)/(T_\infty - T_w)$, dimensionless temperature; λ_f, coefficient of molecular thermal conductivity of the gas; λ_{ef}, effective thermal conductivity of the gas film, determined by (2); ν_f, kinematic viscosity of the gas; ρ_f, ρ_s, density of the gas and the particles, respectively; ρ, mean concentration of the particles over the riser cross section; ρ_w, concentration of the particles at the heat- transfer surface; σ_0, Stefan–Boltzmann constant. Subscripts: cond, conductive; c-c, conductive-convective; ef, effective; f, gas; rad, radiative; s, particles; w, heat-transfer surface; ∞, core of the circulating fluidized bed; *mf*, conditions of the onset of fluidization; t, conditions of floating of a single particle.

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