HEAT TRANSFER BETWEEN A FLUIDIZED BED AND THE SURFACE

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The functional dependence of the coefficient of conductive-convective heat transfer on the determining factors is predicted based on the two-zone model of heat transfer in concentrated dispersed media. The effect of the nonisothermal nature of the fluidized bed on the magnitude of the effective emissivity of the bed is taken into account. General formulas for calculating the coefficients of complex heat transfer were derived and checked in a very wide range of experimental data.

Extensive experimental data have now been obtained on the coefficient of heat transfer between a fluidized bed and the surface under the most diverse conditions. In addition there exist many empirical and semiempirical formulas. These formulas as a rule, generalize different groups of experimental quantities and are applicable in limited ranges of the determining parameters. There are virtually no universal formulas that take into account all components of heat transfer. The best founded and universal formula is the formula of [1]

$$\mathrm{Nu}_{\Sigma}^{\max} = 0.85\,\mathrm{Ar}^{0.19} + 0.006\,\mathrm{Ar}^{0.5}\mathrm{Pr}^{0.33} + 7.3\,\frac{d}{\langle \lambda_f \rangle}\,\sigma\varepsilon_s\varepsilon_w T_w^3, \tag{1}$$

which describes the experimental quantities $\alpha_{\Sigma}^{\max}$ with accuracy acceptable for practical applications in a quite wide range of experimental conditions. Analysis of (1) showed that the greatest disagreement between it and experiment occurs at high pressures of the fluidizing gas (high values of the conductive component) and small values of T_w (low values of the radiant component). This circumstance is connected with the inadequate study of the effect of the pressure on α_{cond} and the effect of the temperature of the layer and the heat-transfer sruface on α_r.

In this work we in these omissions in the modeling of heat transfer and developing universal dependences for calculating a based on a two-zone model which we developed in the last few years for describing external heat transfer in dispersed media [2-4]. The wide range of applicability of this model (fluidized bed, immobile blasted layers, mechanically mixed layers) makes it possible to use this model for implementing the indicated program.

Conductive–Convective Heat Transfer. In [2] an expression is obtained for α_{c-c} for a developed fluidized bed in terms of the parameters of the two-zone model:

$$\alpha_{c-c} = \lambda_f^h / l_0. \tag{2}$$

The following relations were established in [2] for the quantities λ_f^h and ℓ_0

$$\lambda_f^h = \lambda_f + 0.0061\rho_f c_f \frac{u}{m}\, d, \tag{3}$$

$$l_0 = 0.14d(1-m)^{-2/3}. \tag{4}$$

The formula for calculating α_{c-c}

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$$\mathrm{Nu}_{c-c} = 7.2(1-m)^{2/3} + 0.044\,\mathrm{Re}\,\mathrm{Pr}\,\frac{(1-m)^{2/3}}{m}, \tag{5}$$

following from Eqs. (2)-(4), was used in this work as the basic formula for deriving universal dependences for Nu_{c-c} and Nu_{c-c}^{max}.

Comparing the experimental values of α_{c-c} with the values compared from (5) showed that this formula is suitable only for summarizing the experimental data in layers of large ($d \geq 1$ mm) particles. In the case of small particles Eq. (5) gave, as a rule, values of α_{c-c} that are too high; this indictes that the dependence of ℓ_0 (the thickness of the gas interlayer at the heat-transfer surface) on the particle diameter is nonlinear.* For this reason the generalization (4) was made as follows:

$$l_0/d = k_1\,\mathrm{Ar}^{-k_2}(1-m)^{-2/3}, \tag{6}$$

which takes into account the effect of the generalized hydrodynamic characteristic of the particle sin the gas flow (Archimedes number) on the effective thickness of the gas film.

The form (3) for expressing the effective thermal conductivity of the gas film λ_f^h does not take into account the effect of contact heat conduction as well as convection of particles at the heat-transfer surface on the value of the component of λ_f^h that does not depend on the gas velocity (the conductive component). These factors were taken into account by writing λ_f^h in the form†

$$\lambda_f^h = k_3\lambda_f\left(\frac{\lambda_s}{\lambda_f}\right)^{k_4}\left(\frac{\rho_s}{\rho_f}\right)^{k_5}\left(\frac{c_s}{c_f}\right)^{k_6} + k_7\,\mathrm{Ar}^{-k_2^*}\rho_f c_f\,\frac{u}{m}\,d. \tag{7}$$

The expression (6) and (7) together with (2) give

$$\mathrm{Nu}_{c-c} = \frac{k_3}{k_1}\mathrm{Ar}^{k_2}\left(\frac{\lambda_s}{\lambda_f}\right)^{k_4}\left(\frac{\rho_s}{\rho_f}\right)^{k_5}\left(\frac{c_s}{c_f}\right)^{k_6}(1-m)^{2/3} + \frac{k_7}{k_1}\mathrm{Ar}^{k_2-k_2^*}\mathrm{Re}\,\mathrm{Pr}\,\frac{(1-m)^{2/3}}{m}. \tag{8}$$

We obtain for Nu_{c-c}^{max}, based on Eq. (8),

$$\mathrm{Nu}_{c-c}^{max} = k_8\,\mathrm{Ar}^{k_2'}\left(\frac{\lambda_s}{\lambda_f}\right)^{k_4'}\left(\frac{\rho_s}{\rho_f}\right)^{k_5'}\left(\frac{c_s}{c_f}\right)^{k_6'} + k_9\,\mathrm{Ar}^{k_{10}}\mathrm{Pr}. \tag{9}$$

The dependeces (8) and (9) were employed for generalizing a wide range of experimental data on conductive-convective heat transfer.

The problem of determining the value of the coefficients k_i by comparing with experimental data is quite difficult, owing to the unwieldy nature of the expressions (8) and (9). Reliable determination of k_i is also complicated by the existence of a unique "background" — unavoidable errors in the experimental determination of α_{c-c} by different in the heat-transfer surfaces, the methods of measurements, etc.). To reduce to a minimum the effect of this "background" the coefficients k_i were determined in several stages.

We shall study first only the quantities α_{c-c}^{max} is layers of quite small particles, so as to be able to neglect the convective component of the coefficient of heat transfer. The expression for Nu_{cond}^{max} follows from Eq. (9):

*This is evidently connected with the characteristics of the motion of solid particles at the heat-transfer surface under the action of hydroyanmic forces exerted by the fluidizing gas. In an immobile granular layer the dependence of ℓ_0 on d is linear and has a very simple form: $\ell_0 = 0.1\,d$ [4].

†The introduction of Ar^{-k_2*} in the second term takes into account the nonlinear dependence of the filtrational component of λ_f^h on d, which, as in the case with ℓ_0, arises owing to the character of the motion of the particles at the heat-transfer surface.

$$\mathrm{Nu}_{\mathrm{cond}}^{\max} \cong k_8\,\mathrm{Ar}^{k_2'}\left(\frac{\lambda_s}{\lambda_f}\right)^{k_4'}\left(\frac{\rho_s}{\rho_f}\right)^{k_5'}\left(\frac{c_s}{c_f}\right)^{k_6'}. \tag{10}$$

This form is extremely convenient for analysis and makes it possible to employ a simple and effective method for determining the exponents in Eq. (10); this methods reduces to a minimum the drawbacks that arise with the use of traditional methods (for exmaple, the method of least squares) owing to the existence of the above-mentioned "background." The essence of the method consists of the follwoing. The ratios of the absolute experimental values of $\alpha^{\max}_{\mathrm{cond}}$ rather than the absolute values themselves are employed, and the comparison is made under identical experimental conditions. Experiments in which the simplexes λ_S/λ_f, ρ_S/ρ_f and C_S/C_f have extremal values are chosen; this obviously makes it possible to make a more reliable determination of the coefficients in (10). In accordance with this the chosen published data were employed in the following form:

$$\begin{aligned}
&(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{Cu}}/(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{sand}} = 1{,}27 \text{ (fluidizing medium — idem) [5, c. 217]},\\
&(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{Pb}}/(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{sand}} = 1 \text{ (fluidizing medium — idem) [6, c. 307]},\\
&(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{He}}/(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{air}} = 3 \text{ (particles — idem) [7, c. 469]},\\
&(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{H}}/(\alpha_{\mathrm{cond}}^{\max})_{\mathrm{air}} = 3{,}45 \text{ (particle — idem) [7, c. 469]}.
\end{aligned} \tag{11}$$

Substituting into Eq. (11) the expression (10) with specific values of λ, ρ, and C gives a system of four equations. Which after taking the logarithm have the following form:

$$\begin{aligned}
&1{,}27k_2' + 3{,}02k_4' + 1{,}27k_5' - 0{,}72k_6' = 0{,}24,\\
&1{,}51k_2' + 3{,}85k_4' + 1{,}51k_5' - 1{,}81k_6' = 0,\\
&1{,}9k_2' + 1{,}7k_4' - 1{,}9k_5' + 1{,}66k_6' = 0{,}6,\\
&1{,}16k_2' + 1{,}94k_4' - 2{,}6k_5' + 2{,}66k_6' = 0{,}71.
\end{aligned} \tag{12}$$

The solution of (12) gave: $k_2' \approx 0.16$; $k_4' \approx 0.03$; $k_5' \approx 0.14$; and $k_6' \approx 0.30$. The generalization of the experimental data of [8-18] based on the values of $\alpha^{\max}_{c\text{-}c}$, performed based on Eq. (9) using the values obtained for the coefficients k_i, gave the dependence*

$$\mathrm{Nu}_{c-c}^{\max} = 0{,}4\,\mathrm{Ar}^{0{,}16}\left(\frac{\rho_s}{\rho_f}\right)^{0{,}14}\left(\frac{c_s}{c_f}\right)^{0{,}30} + 0{,}0013\mathrm{Ar}^{0{,}63}\,\mathrm{Pr}. \tag{13}$$

The equation (13) is valied in the following range of values of the parameters: $0.1 \le p \le 10.0$ MPa; $1 \le d \le 4$ mm ($1.4\cdot10^2 \le \mathrm{Ar} \le 1.1\cdot10^7$). The standard deviation of the experimental points from the points calculated using Eq. (13) is equal to 14%. As one can see, the exponents of Ar and ρ_S/ρ_f are close; this is what gives the very weak pressure dependence of $\mathrm{Nu}^{\max}_{\mathrm{cond}}$. This corresponds to the well-known experimental fact that the pressure dependence of the heat-transfer coefficient in layers of small particles is weak [1] and confirms the fact that the generalization (13) obtained is physically well-founded.

The exponents in Eq. (8) were also found in several stages. First only the experimental data on the heat transfer for a single horizontal pipe in layers of particles of different diameter at atmospheric prssure and low temperatures, when the simplexes ρ_S/ρ_f remained virtually constant, were processed. This made is possible to determine with maximum reliability the dependence of the conductive component on the number Ar (the diameter of the particles). The generalization of the experimental data of [8-14] based on Eq. (8) neglecting the simplexes λ_S/λ_f, β_S/ρ_f and C_S/C_f

*Because the exponents of the complex λ_S/λ_f is small the cofactor $(\lambda_S'/\lambda_f)^{0.03}$ was neglected in the processing of the experimental data.

$$\mathrm{Nu}_{c-c} = 2.62\mathrm{Ar}^{0.1}(1-m)^{2/3} + 0.033\,\mathrm{RePr}\,\frac{(1-m)^{2/3}}{m}\,. \tag{14}$$

The formula (14) describes the experimental data with a standard deviation of 17%, and was checked in the range $\mathrm{Ar} = 1.4\cdot10^2-6.8\cdot10^6$.

At the second stage the experimental data at high pressures [15, 16] were also employed and the general sample of data on the quantities α_{c-c} [8-16] was made based on Eq. (8). In so doing it was assumed that $k_2 = 0.1$, $k_4 = 0$, and $k_6 = k_2 + k_5$. The last equality is based $k_6' = k_2' + k_5'$. In addition, it follows from simple physical consideration that it is best to use not the specific but rather the volume heat capacities of the phases. Since the number Ar contains the factor $\frac{\rho_s}{\rho_f} - 1 \simeq \frac{\rho_s}{\rho_f}$, the condition $k_6 = k_2 + k_5$ results in the appearance of the physically well-founded factor $(\rho_S c_S/\rho_f c_f)^{0.1+k_5}$. The processing of the experimental data on α_{c-c} gave the following correlation:

$$\mathrm{Nu}_{c-c} = 0.74\,\mathrm{Ar}^{0.1}\left(\frac{\rho_s}{\rho_f}\right)^{0.14}\left(\frac{c_s}{c_f}\right)^{0.24}(1-m)^{2/3} + 0.046\,\mathrm{Re}\,\mathrm{Pr}\,\frac{(1-m)^{2/3}}{m}, \tag{15}$$

which generalizes the experimental values of α_{c-c} with a standard deviation of 22%. The formula (15) was checked in the ranges $0.1 \le d \le 4$ mm $(1.4\cdot10^2 \le \mathrm{Ar} \le 1.1\cdot10^7)$.

Conductive–Convective–Radiative Heat Transfer. To extend the dependences (13) and (15) obtained above to the case of high temperatures they must be supplemented by the radiative component of the heat-transfer coefficient

$$\alpha_r = \sigma(T_\infty^2 + T_w^2)(T_\infty + T_w)\left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_e} - 1\right)^{-1}. \tag{16}$$

The problem of taking into account correctly the radiative transfer reduces, as is well known, to determining the apparent (effective) emissivity of the fluidized bed ε_e, which takes into account the effect of cooling (heating) of the particles at the heat-transfer surface.

The functional dependence of ε_e on the temperature of the core of the bed and the heat-transfer sruface was established in [15]:

$$\frac{\varepsilon_e}{\varepsilon_b} = (1-A)\left(\frac{T_w}{T_\infty}\right)^4 + A, \quad \frac{T_w}{T_\infty} \leqslant 1^*. \tag{17}$$

The experimental data of [19] on ε_e in fluidized beds of corundum were synthesized on the basis of (17). The following expression was obtained for the coefficient A (the parameter of isothermicity):

$$A = 1 - \exp(-0.16\mathrm{Ar}^{0.26}), \quad \mathrm{Ar} \geqslant 1.22\cdot10^2. \tag{18}$$

As follows from Eq. (18), for $\mathrm{Ar} \ge 10^5$ the parameter of isothermicity $A \approx 1$ and $\varepsilon_e \approx \varepsilon_b$, which corresponds to a completely isothermal layer. The obtained result agrees with the results of [20], where it was shown that intensive interphase heat transfer in layers of particles with $d > 1$ mm compensates to a significant extent the heat lost by particles owing to heat conduction to the wall. The experimental data of [21] on heat transfer of high-alumina particles of fireclay at high temperatures also indicate that particles with $d > 1$ mm cool insignificantly and that this effect must be taken into account in layers of small ($d \le 0.5$ mm) particles.

The generalization of the experimental data of [8-16, 19, 22], including also the experiments at high temperatures [19, 22], gave the following dependence

$$\mathrm{Nu}_\Sigma = 0.85\,\mathrm{Ar}^{0.1}\left(\frac{\rho_s}{\rho_f}\right)^{0.14}\left(\frac{c_s}{c_f}\right)^{0.24}(1-m)^{2/3} + 0.046\,\mathrm{RePr}\,\frac{(1-m)^{2/3}}{m} + \frac{d}{\langle\lambda_f\rangle}\,\sigma^*(T_\infty^2 + T_w^2)(T_\infty + T_w). \tag{19}$$

*In the case $T_w/T_\infty > 1$ Eq. (17) has the form $\varepsilon_e/\varepsilon_b = (1-A)/(T_\infty/T_w)^4 + A$.

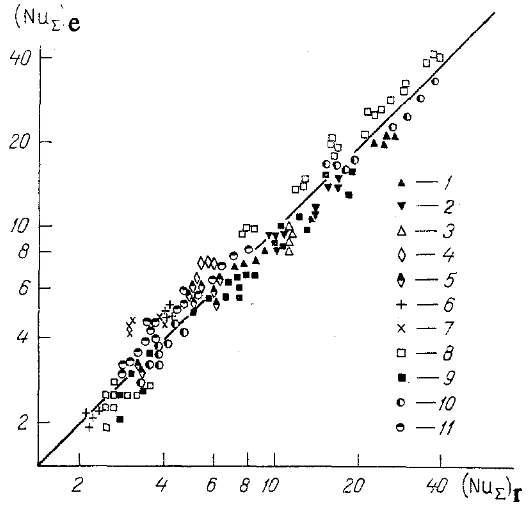

Fig. 1. The synthesis of the experimental data on the values of the heat-transfer coefficient in a fluidized bed: 1) [8] (d = 1.3; 4 mm); 2) [9] (d = 2; 3) [10] (d = 1.6 mm); 4) [11] (d = 0.7 mm): 5) [12] (d = 0.25; 0.62; 0.98 mm); 6) [13] (d = 0.1; 0.4 mm); 7) [14] (d = 0.26; 0.35 mm); 8) [15] (d = 0.126; 1.22 mm; p = 0.1-8.1 MPa, T_W = 373 K; T_∞ = 300 K); 9) [16] (d = 0.75; 1.5 mm; p = 0.5-10 MPa; T_W = 320 K; T_∞ = 420 k); 10) [19] (d = 0.5; 6 mm; p = 0.1 MPa; T_W = 373-1373 K; T_∞ = 1073; 1473 K); 11) [22] (d = 0.35; 0.63; 1.25 mm; p = 0.1 MPa; T_W = 433-1023 K; T_∞ = 1123 K); 1-7) atmospheric pressure and room temperature.

The formula (19) corresponds to the indicated experimental data with standard deviation of 18% (Fig. 1). It was checked in the following range of values of the parameters: $0.1 \le p \le 10.0$ MPa; $T_\infty \le 1473$ K; $T_W \le 1373$ K; $0.1 \le d \le 6.0$ mm ($1.4 \cdot 10^2 \le \mathrm{Ar} \le 1.1 \cdot 10^7$).

The generalization of the experimental data on the values of Nu_Σ^{max} [8-19, 21-27] has the form

$$\mathrm{Nu}_\Sigma^{\max} = 0.36\,\mathrm{Ar}^{0.16}\left(\frac{\rho_s}{\rho_f}\right)^{0,14}\left(\frac{c_s}{c_f}\right)^{0,30} + 0{,}0013\,\mathrm{Ar}^{0.63}\,\mathrm{Pr} + \frac{d}{\langle \lambda_f \rangle}\,\sigma^* (T_\infty^2 + T_w^2)(T_\infty + T_w). \qquad (20)$$

The correlation (20) is valid for the following conditions: $0.1 \le p \le 10.0$ MPa; $T_\infty \le 1713$ K; $T_W \le 1373$ K; $0.1 \le d \le 6.0$ mm ($1.4 \cdot 10^2 \le \mathrm{Ar} \le 1.1 \cdot 10^7$). It describes the experimental results with a standard deviation of 16% (Fig. 2). The emissivity of an isothermal fluidized bed, appearing in Eq. (19), was calculated from the formula [28]

$$\varepsilon_b = 1.63\,\frac{m - m_{mf}}{1 - m_{mf}}\,\varepsilon_s^{0.310} + \left(1 - 1.63\,\frac{m - m_{mf}}{1 - m_{mf}}\right)\varepsilon_s^{0.485}. \qquad (21)$$

To calculate Nu_Σ^{max} from Eq. (20) the following dependence is employed [29]:

$$\varepsilon_b = \varepsilon_s^{0.4}. \qquad (22)$$

It should be noted that in the calculations performed the average transmission of the layer was determined with the help of the following expression:

$$m = m_{mf} + 1.56\,\frac{\mathrm{Re} - \mathrm{Re}_{mf}}{\mathrm{Ar}^{1/2}}\,(1 - m_{mf}),$$

for large particles (d > 1 mm) [15] and

$$m = 1 - \frac{1 - m_{mf}}{1 + 0.7\,(H_{mf}/D)^{1/2}\,\mathrm{Fr}^{1/3}}\,.$$

for small particles (d < 1 mm) [30].

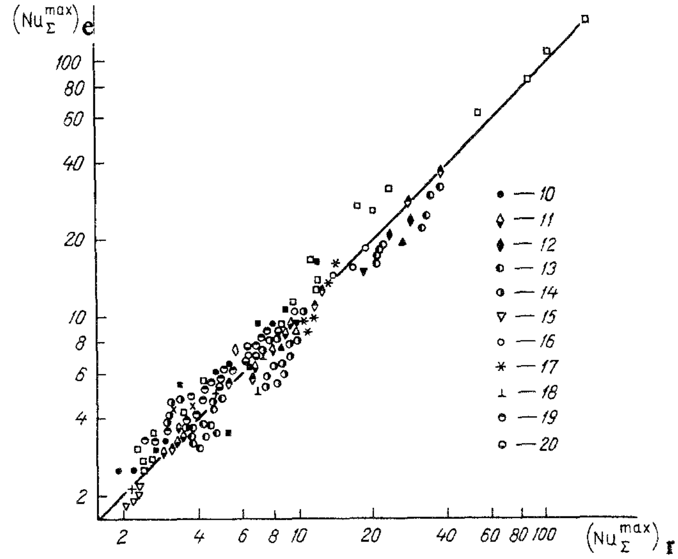

Fig. 2. Generalization of the experimental data on the maximum values of the heat-transfer coefficient in a fluidized bed: 1-9) see Fig. 1; 10) [17] (d = 0.12-1.16 mm; p = 0.1 MPa); 11, 12) [18] (d = 0.16-2.37 mm; p = 0.1-0.93 MPa); 13) [19] see 10 in Fig. 1; 14) [23] (d = 0.34-1.66 mm, p = 0.1 MPa; T_W = 423-573 K; T_∞ = 573-1173 K); 15) [24] (d = 0.12; 0.32 mm; p = 0.1 MPa; T_W = 373-423 K; T_∞ = 473-673 K); 16) [25] (d = 1.05-4 mm; p = 0.1 MPa; T_W = 303 K; T_∞ = 1073-1273 K); 17) [21] (d = 1.22; 1.73 mm; p = 0.1 MPa; T_W = 423-1573 K; T_∞ = 1223-1573 K); 18) [27] (d = 0.37; 1.25 mm; p = 0.1 MPa; T_W = 337-628 K; T_∞ = 573-1273 K); 19) [22] see Fig. 11 Fig. 1; 20) [26] (d = 0.8; 1.8 mm; p = 0.1 MPa; T_W = 373 K; T_∞ = 753-1713 K); 10-12) at room temperatures.

In accordance with the analysis performed in [25] in Eqs. (19) and (20) the values of the thermophysical characteristics of the gas at the average temperature $(T_\infty + T_W)/2$ are used. The values of the porosity and the number Ar in Eq. (18) are calculated for the temperature of the core of the layer T_∞.

The dependences (13)-(15), (19), and (20) established in this work were checked in wide range of experimental conditions and can be recommended for calculating the heat-transfer coefficients in industrial apparatus with a fluidized bed.

NOTATION

A, parameter of isothermicity; $Ar=\frac{gd^3}{\nu_f^2}\left(\frac{\rho_s}{\rho_f}-1\right)$, Archimedes number; c, specific heat capacity; $d=1/\Sigma(\eta_i/d_i)$, where d_i is the size of the i-th fraction; g, acceleration of gravity; ℓ_0, effective thickness of the gas film; m, porosity of the layer; $Nu=\alpha d/\langle\lambda_f\rangle$, Nusselt's number; p pressure; $Pr=c_f\eta_f/\langle\lambda_f\rangle$, Pradtl's number; $Re=ud/\nu_f$, Reynolds number; T, temperature; u, rate of filtration; α, heat-transfer coefficient; ε, emissivity; η_i, mass fraction of the i-th fraction of the particle; η_f, dynamic viscosity of the gas; λ, thermal conductivity; λ_s^h, horizontal thermal conductivity of the granular layer; ν_f, kinematic viscosity of the gas; ρ, density; σ, Stefan—Boltzmann constant; $\sigma^*=\sigma/(1/\varepsilon_w+1/\varepsilon_e-1)$; $\langle\cdot\rangle$, that the enclosed quantity is evaluated at the temperature $(T_\infty + T_W)/2$; H, height of the layer; D, diameter of the column; $Fr=(u-u_{mf})^2/gH_{mf}$, Froude's number. The indices are as follows: v — fluidized bed; cond — conductive; conv — convective; c-c — conductive-convective; e — effective; f — gas; mg — the start of the fluidization; r — radiative; s — particles; w — heat-transfer surface; ∞ — the core of the fluidized bed; Σ — total; exp — experimental; p — computed; max — maximum.

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