Journal of Engineering Physics and Thermophysics, Vol. 67, Nos. 5-6, 1994

HEAT EXCHANGE BETWEEN A FLUIDIZED BED AND SMALL-SIZED BODIES

Yu. S. Teplitskii

UDC 66.096.5

On the basis of the two-zone model, a procedure is developed for calculating the complex heat exchange of a probe of small dimensions (comparable with the diameter of the bed particles). The procedure takes into account the influence of the fluidizing agent pressure.

When studying processes of combustion of a solid organic fuel in fluidized-bed furnaces, it is necessary to know the laws governing heat exchange between a reacting coal particle and the surrounding high-temperature bed of inert material. Under such conditions the heat exchange has a complex conductive-convective-radiative nature that, apart from other familiar factors, is influenced by the size of the carbon particle.

The literature contains rather reliable experimental data and corresponding correlations obtained for the most part under conditions of heat exchange of small-sized mobile probes in cold laboratory facilities at atmospheric pressure [1–5]. The limited region for the application of these results precludes using them with sufficient justification for calculating fluidized-bed furnaces. In this connection, in the present work we formulate the problem of using earlier adequately verified notions about the mechanism of external heat exchange in a fluidized bed within the framework of the two-zone model [6] to establish the laws governing complex heat exchange of probes of small dimensions (comparable with the diameter of the bed particles) and obtain generalized correlations suitable for calculating the heat exchange of a chemically reacting coal particle with a high-temperature fluidized bed of inert particles.

First, we obtain the dependence of the heat transfer coefficient of a small probe on the determining factors at moderate temperatures and pressures. The main model relation that determines the value of the conductive-convective heat transfer coefficient has the form [6]

$$\alpha_{cc} = \lambda_f^h / l_0 , \tag{1}$$

where λ_f^h is the effective thermal conductivity of the boundary layer; l_0 is the thickness of the latter. In the case of a massive probe ($D/d >> 1$) the following equation was obtained in [7]:

$$\mathrm{Nu}_{cc} = \frac{\alpha_{cc} d}{\lambda_f^k} = 2.62\,\mathrm{Ar}^{0.1}\,(1-\varepsilon)^{2/3} + 0.033\,\mathrm{Re}\,\mathrm{Pr}\,\frac{(1-\varepsilon)^{2/3}}{\varepsilon} . \tag{2}$$

It can easily be shown on the basis of Eq. (1) that expression (2) is equivalent to the equations

$$\lambda_f^h = \lambda_f^k + 0.0125\,\mathrm{Ar}^{-0.1}\, c_f \rho_f u d/\varepsilon , \tag{3}$$

$$l_0 = 0.38\,\mathrm{Ar}^{-0.1}\,(1-\varepsilon)^{-2/3}\, d . \tag{4}$$

To generalize Eq. (2) to the case of small probes ($D \geq d$), we take into account the dependence of the effective thickness of the boundary layer on the simplex D/d. The existence of such a relationship follows from the simplest

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus," Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 67, Nos. 5-6, pp. 428-432, November-December, 1994. Original article submitted April 9, 1993.

 1062-0125/94/6756-1062$12.50

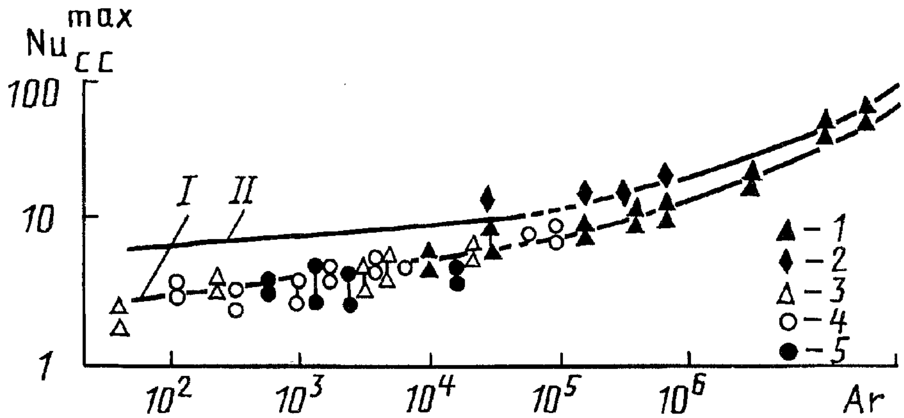

Fig. 1. Dependence of Nu_{cc}^{max} on Ar (small-sized probes): 1) data of [3]; 2) [1], $D/d = 1$; 3) [4]; 4) [5]; 5) [2]; I) calculation by Eq. (7); II) calculation by Eq. (7) for $D/d = 1$.

geometric considerations,* which lead to the conclusion of a decrease in l_0 with a decrease in the probe diameter. Since, according to Eq. (1), $\alpha_{cc} \sim 1/l_0$, the dependence of l_0/d on D/d should be determined unambiguously by the dependence of the coefficient α_{cc} on this simplex. Analysis of the literature data [3] showed that $\alpha_{cc} \sim (D/d)^{-0.2}$; consequently, $l_0/d \sim (D/d)^{0.2}$. This permits one to generalize the model expression (4) to the case of small values of the ratio D/d:

$$l_0 = 0.38k\,\mathrm{Ar}^{-0.1}\,(1-\varepsilon)^{2/3}\,(D/d)^{0.2}\,d\,. \tag{5}$$

We can easily determine the value of the coefficient k from the limiting condition: $k(D/d)_\infty^{0.2} = 1$, where $(D/d)_\infty$ is the asymptotic value of D/d at which the quantity α_{cc} ceases to depend on D/d. According to [3, 5], $(D/d)_\infty = 12-13$ ($\mathrm{Ar} \geq 1.5\cdot 10^5$, coarse particles) and $(D/d)_\infty = 100-300$ ($\mathrm{Ar} < 1.5\cdot 10^5$, fine particles). This gives the following estimate for k: $k = 0.4-0.6$.

With allowance for Eqs. (1), (3), and (5), we obtain the following equation for the coefficient of conductive-convective heat transfer of a small-sized probe:

$$\mathrm{Nu}_{cc} = \frac{1}{k}\left(\frac{D}{d}\right)^{-0.2}\left(2.62\,\mathrm{Ar}^{0.1}\,(1-\varepsilon)^{2/3} + 0.033\,\mathrm{Re}\,\mathrm{Pr}\,\frac{(1-\varepsilon)^{2/3}}{\varepsilon}\right). \tag{6}$$

Equation (6) can be simplified substantially by considering a mobile probe, when we can assume in Eq. (6) that $\varepsilon = \varepsilon_{mf}$ and $\mathrm{Re} = \mathrm{Re}_{mf}$. Using the use of the well-known Todes formula [8] for the relationship between Re_{mf} and Ar, Eq. (6) takes the form (for $\varepsilon_{mf} = 0.4$ and $\mathrm{Pr} = 0.71$)

$$\mathrm{Nu}_{cc}^{max} = \frac{1}{k}\left(\frac{D}{d}\right)^{-0.2}\left(1.86\,\mathrm{Ar}^{0.1} + 0.042\,\frac{\mathrm{Ar}}{1400 + 5.22\sqrt{\mathrm{Ar}}}\right). \tag{7}$$

A comparison of the available experimental data [1–5] with those predicted by Eq. (7) is presented in Fig. 1. It was assumed that $1/k = 2$ ($\mathrm{Ar} < 1.5\cdot 10^5$), $1/k = 1.67$ ($\mathrm{Ar} \geq 1.5\cdot 10^5$. The standard deviation of the test data from those predicted is 9%. Formula (7) is valid provided that $D/d \geq 1$.

In the process of chemical interaction with the surrounding gas the carbon particles become smaller than the inert particles. In connection with this it is also necessary to have recommendations for calculating the heat transfer coefficient when $D < d$. One realizes that it is virtually impossible to obtain reliable experimental data in

* Within the framework of the present two-zone model of heat exchange the thickness of the boundary layer of the gas film is determined directly by the magnitude of the zone of elevated porosity at the heat exchange surface [6].

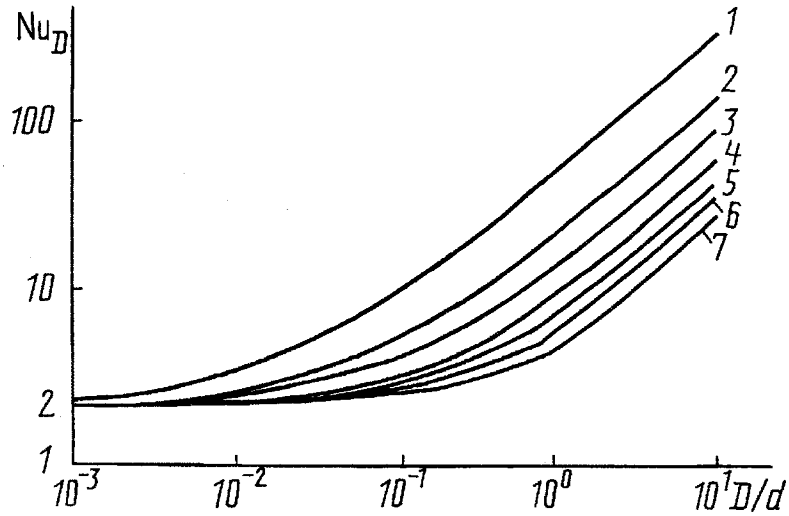

Fig. 2. Dependence of $(Nu_{cc}^{max})_D = \alpha_{cc}^{max} D/\lambda_f^k$ on the ratio D/d for different values of Ar: 1–7) Ar = 10^7, 10^6, 10^5, 10^4, 10^3, 10^2, 10^1, respectively (calculation by Eq. (8)).

this region. A theoretical analysis of the heat exchange of very small particles-probes is also hindered. In [9] an attempt was made to obtain a computational correlation on the basis of the not very reasonable assumption that in this case the intensity of heat exchange is proportional to the maximum possible number of points of contact between the particle-probe and the inert particles. In the opinion of the present author, the assumption made in [10] is physically more valid. According to it, very fine "active" particles move in the bed in the mode of pneumatic transport in the interstices between the inert particles. In such a case, it is recommended that heat exchange be calculated from the well-known formulas for a single motionless sphere immersed in a gas flow. This recommendation is made for the condition $D \ll d$. In the region of large values of D (but again with $D < d$), the authors of [10] had to perform in addition an interpolation. Because of this, the resulting computational relations turned out to be very cumbersome and inconvenient for practical use.

An analysis of the process of heat exchange of a particle-probe that was performed by us for $D < d$ on the basis of Eq. (7) made it possible to obtain an extremely simple interpolation formula (see Fig. 2)

$$(Nu_{cc}^{max})_D = \alpha_{cc} D/\lambda_f^k = 2\,(1 - A^* D/d) + \frac{1}{k}\left(\frac{D}{d}\right)^{0.8} \times$$

$$\times \left(1.86\,Ar^{0.1} + 0.042\,\frac{Ar}{1400 + 5.22\sqrt{Ar}}\right), \qquad (8)$$

where $A^* = d/D$, $D > d$; $A^* = 1$, $D \le d$. This formula describes correctly the limiting situations $D \gg d$ and $D \ll d$. In the intermediate region the values of α_{cc} calculated by Eq. (8) agree satisfactorily with those obtained in [10].

Now, it is not difficult to extend Eq. (8) to the case of elevated pressures for the fluidizing gas. In [7] a dependence was obtained for Nu_{cc} that describes the results of experiments on heat exchange of massive probes in beds under pressure ($0.1 \le p \le 10.0$ MPa):

$$Nu_{cc} = 0.74\,Ar^{0.1}\left(\frac{\rho_s}{\rho_f}\right)^{0.14}\left(\frac{c_s}{c_f}\right)^{0.24}(1 - \varepsilon)^{2/3} + 0.046\,Re\,Pr\,\frac{(1 - \varepsilon)^{2/3}}{\varepsilon}. \qquad (9)$$

Repeating what was said when formula (8) was obtained and using Eq. (9) as a basis, we can easily find a formula similar to Eq. (8):

$$(\mathrm{Nu}_{cc}^{\max})_D = 2\,(1 - A^* D/d) + \frac{1}{k}\left(\frac{D}{d}\right)^{0.8}\left(0.53\,\mathrm{Ar}^{0.1}\left(\frac{\rho_s}{\rho_f}\right)^{0.14}\times\right.$$

$$\left.\times\left(\frac{c_s}{c_f}\right)^{0.24} + 0.058\,\mathrm{Ar}/(1400 + 5.22\sqrt{\mathrm{Ar}}\,)\right), \tag{10}$$

which describes the conductive-convective heat exchange of a moving particle under normal and elevated pressures.

At high temperatures the coefficient of conductive-convective heat transfer should be supplemented with the radiative component

$$(\mathrm{Nu}_r)_D = \frac{D}{\lambda_f^k}\sigma^*\,(T_\infty^2 + T_p^2)\,(T_\infty + T_p)\,, \tag{11}$$

in which, according to the recommendations given in [7, 11, 12],

$$\varepsilon_e/\varepsilon_b = A + (1 - A)\,(T_p/T_\infty)^4 \tag{12}$$

for $T_p \le T_\infty$,*

$$A = 1 - \exp\,(-\,0.16\,\mathrm{Ar}^{0.26})\left(1 - \exp\left(-\frac{D}{d}\right)\right), \quad \mathrm{Ar} \ge 120\,; \tag{13}$$

$$\varepsilon_b = \varepsilon_s^{0.485}\,. \tag{14}$$

We note that in [7] the expression for A obtained for $D/d \gg 1$ does not contain the factor $1 - \exp\,(-D/d)$. The appearance of the latter in Eq. (13) is an attempt to take into account in the simplest form the dependence of the degree of "superheating" of inert particles located near the "active" particle-probe on the simplex D/d. The factor $1 - \exp\,(-D/d)$ has an interpolation character (just as, by the way, all the other relations obtained in that work) and gives correct limiting values of A for the cases $D/d \gg 1$ and $D/d \ll 1$.

Thus, to calculate the coefficient of complex heat transfer between a mobile particle-probe and a fluidized bed, we can recommend the following formula

$$(\mathrm{Nu}_\Sigma^{\max})_D = 2\,(1 - A^* D/d) + \frac{1}{k}\left(\frac{D}{d}\right)^{0.8}\left(0.53\,\mathrm{Ar}^{0.1}\left(\frac{\rho_s}{\rho_f}\right)^{0.14}\times\right.$$

$$\left.\times\left(\frac{c_s}{c_f}\right)^{0.24} + 0.058\,\frac{\mathrm{Ar}}{1400 + 5.22\sqrt{\mathrm{Ar}}}\right) + \frac{D}{\lambda_f^k}\sigma^*\,(T_\infty^2 + T_p^2)\,(T_\infty + T_p)\,. \tag{15}$$

The region of applicability of relation (15) is $1.2\cdot 10^2 \le \mathrm{Ar} \le 1.1\cdot 10^7$, $0.1 \le p \le 10.0$ MPa, $0.1 \le d \le 6.0$ mm, $T_\infty \le 1200°\mathrm{C}$, $T_p \le 1200°\mathrm{C}$.

The obtained generalized correlations (8), (10), (15) together with relations (12)-(14) can be used quite justifiably for calculating the combustion of solid fuel particles in fluidized-bed furnaces and also other processes accompanied by chemical interaction of a small portion (1–10%) of the "active" particles with the gas blown through.

---

* In the case of $T_p > T_\infty$ Eq. (12) has the form $\varepsilon_e/\varepsilon_b = A + (1 - A)(T_\infty/T_p)^4$.

NOTATION

A^*, parameter ($A^* = d/D$, $D > d$; $A^* = 1$, $D \le d$); $\mathrm{Ar} = gd^3(\rho_s/\rho_f - 1)/\nu_f^2$, Archimedes number; c, specific heat; D, probe diameter; d, diameter of the bed particles; g, free fall acceleration; l_0, effective thickness of the boundary layer (of the gas film); $\mathrm{Nu} = \alpha d/\lambda_f^k$, $\mathrm{Nu}_D = \alpha D/\lambda_f^k$, Nusselt numbers; p, pressure; $\mathrm{Pr} = c_f\eta_f/\lambda_f^k$, Prandtl number; $\mathrm{Re} = ud/\nu_f$, Reynolds number; u, filtration rate; T, temperature; α, heat transfer coefficient; ε, porosity; ε_s, emissivity of inert particles; ε_p, emissivity of the probe surface; η_f, ν_f, dynamic and kinematic gas viscosities; ρ, density; λ_f^h, effective thermal conductivity of the boundary layer; λ_f^k, molecular thermal conductivity of the fluidizing gas; σ, Stefan–Boltzmann constant; $\sigma^* = \sigma/(1/\varepsilon_p + 1/\varepsilon_e - 1)$. Subscripts: f, gas; s, particles; mf, minimum fluidization; b, fluidized bed; cc, conductive-convective; e, effective; r, radiative; ∞, core of the fluidized bed; Σ, overall. Superscripts: h, boundary layer; k, molecular; max, maximum.

REFERENCES

1. J. Vanderchuren and C. Delvosalle, Chem. Eng. Sci., **35**, No. 8, 1741-1748 (1980).
2. G. M. Rios and C. Gilbert, Entropie, No. 106, 67-75 (1982).
3. G. I. Pal'chenok and A. I. Tamarin, Inzh.-Fiz. Zh., **45**, No. 3, 427-433 (1983).
4. W. Prins, W. Draijer, and W. P. N. van Swaaij, Proc. 16th ICHMT Symp., Dubrovnik (1984), pp. 317-331.
5. V. A. Borodulya, G. I. Pal'chenok, G. G.Vasil'ev, et al., Problems of Heat and Mass Transfer in the Modern Technology of Burning and Gasification of a Solid Fuel (Proceedings of the Int. School-Seminar, Pt. 2, Heat and Mass Transfer Institute of the Academy of Sciences of the BSSR) [in Russian], Minsk (1988), pp. 3-23.
6. V. A. Borodulya, Yu. S. Teplitsky, Yu. G. Yepanov, and I. I. Markevich, Int. J. Heat Mass Transfer, **32**, No. 9, 1595-1604 (1989).
7. V. A. Borodulya, Yu. S. Teplitskii, I. I. Markevich, et al., Inzh.-Fiz. Zh., **58**, No. 4, 597-604 (1990).
8. M. E. Aerov, and O. M. Todes, Hydraulic and Thermal Foundations of the Operation of Apparatus with a Stationary and Fluidized Granular Bed [in Russian], Leningrad (1968).
9. A. P. Baskakov, N. F. Filippovskii, V. A. Munts, and A. A. Ashikhmin, Inzh.-Fiz. Zh., **52**, No. 5, 788-793 (1987).
10. G. I. Pal'chenok, G. G. Vasil'ev, A. F. Dolidovich, et al., Heat and Mass Transfer MIF-92 (Heat and Mass Transfer in Disperse Systems) [in Russian], Vol. 5, Minsk (1992), pp. 172-176.
11. V. A. Borodulya, V. L. Ganzha, and V. I. Kovenskii, Hydrodynamics and Heat Transfer in a Pressurized Fluidized Bed [in Russian], Minsk (1982).
12. V. A. Borodulya, V. I. Kovenskii, and K. E. Makhorin, in: Heat and Mass Transfer in Disperse Systems, Collected Papers of the Heat and Mass Transfer Institute of the Academy of Sciences of the BSSR [in Russian], Minsk (1982), pp. 3-20.