NOTATION

$\mathrm{Re}=\frac{ud}{\psi\nu}$; $\mathrm{Nu}=jd/D(c_o-c_r)$; $\vartheta_{\mathrm{Nu}}=\frac{\sigma}{\mathrm{Nu_f}}100$; $\sigma=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{Nu}_i-\mathrm{Nu_{av}})^2}$; $\delta=k/\bar{\beta}$; c, concentration; D, diffusion coefficient; d, diameter of a grain; j, specific flow of the material to the surface of the grain; k, reaction rate constant; s, external surface of the grain; $\Delta s(\mathrm{Nu})$, distribution function of the local mass-transfer coefficients on the external surface of the grain; u, rate of flow referred to the whole cross section of the layer; w, rate of chemical reaction; ψ, minimum useful cross section (0.17); β, mass-transfer coefficient; and ν, coefficient of kinematic viscosity. Indices: f and K, front and rear parts of the surface; av, average value; max, maximum value; r, surface; and o, free volume of the layer.

LITERATURE CITED

1. V. A. Kirillov, Yu. Sh. Matros, and M. G. Slin'ko, Teor. Osn. Khim. Tekhnol., 5, 226 (1971).
2. V. A. Kirillov, Yu. Sh. Matros, V. N. Sorokin, M. A. Kasamanyan, and M. G. Slin'ko, Dokl. Akad. Nauk SSSR, 206, 1409 (1972).
3. É. N. Brandes, E. V. Badatov, V. E. Nakoryakov, M. G. Slin'ko, and Yu. Sh. Matros, Teor. Osn. Khim. Tekhnol., 7, 395 (1973).
4. B. W. Gillespie, AIChE J., 14, 486 (1968).
5. K. R. Jolls and T. J. Hanratty, AIChE J., 15, 199 (1969).
6. I. W. Rhodes and F. H. Peebles, AIChE J., 11, 481 (1965).
7. A. I. Karabelas, T. H. Wagner, and T. Hanratty, J. Chem. Eng. Sci., 28, 673 (1973).
8. S. S. Zabrodskii and L. K. Zhitkevich, Collected Papers of the All-Union Conference on Heat and Mass Transfer, Minsk (1968).
9. E. V. Badatov, M. G. Slin'ko, and V. E. Nakoryakov, Teor. Osn. Khim. Tekhnol., 5, 687; 6, 868 (1970).
10. D. A. Frank-Kamenetskii, Diffusion and Heat Transfer in Chemical Kinetics, Plenum Publ. (1969).
11. V. I. Lugovskoi and Yu. Sh. Matros, in: Khimreaktor-5, No. 1, Ufa (1974), p. 166.
12. V. I. Lugovskoi, Yu. Sh. Matros, V. A. Kirillov, and M. G. Slin'ko, Teor. Osn. Khim. Tekhnol., 8, No. 4 (1974).

EXPERIMENTAL INVESTIGATION OF THE RADIANT AND CONDUCTIVE–CONVECTIVE COMPONENTS OF EXTERNAL HEAT EXCHANGE IN A HIGH-TEMPERATURE FLUIDIZED BED

O. M. Panov, A. P. Baskakov,
Yu. M. Goldobin, N. F. Filippovskii,
and Yu. S. Mazur

UDC 66.096.5:66.045.2

The results of the experimental investigation of the components of complex external heat exchange in a high-temperature fluidized bed, by means of a radiometer and two α calorimeters with a different degree of surface blackness, are given.

In order to separate complex heat exchange into radiant and conductive–convective components, in this paper the combined heat-transfer coefficients to two α calorimeters, differing only in the degree of surface blackness, were measured. Each α calorimeter was a box with dimensions of $80 \times 80 \times 40$ mm, made of Nichrome with a thickness of 5 mm, and filled inside with kaolin wadding.

The heat-transfer coefficients were determined by the heating or cooling rate of the side walls of the α calorimeter, in which a thermocouple was calked. In order to reduce thermal inflows from the end walls of the α calorimeter, which could be heated up differently than the side walls because of differences in their flow

S. M. Kirov Ural Polytechnic Institute, Sverdlovsk.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 36, No. 3, pp. 409–415, March, 1979. Original article submitted March 24, 1978.

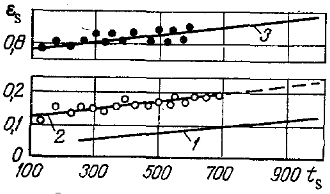

Fig. 1. Dependence of the degree of surface blackness on the temperature t_s, °C: 1) for polished platinum [4]; 2) for the "white" calorimeter; 3) for oxidized Nichrome [1] ("black" α calorimeter). The points are the experimental data.

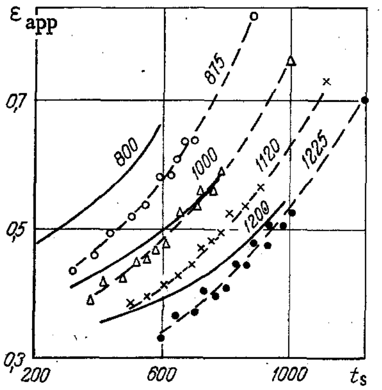

Fig. 2. Effect of temperature of heat-exchange surface t_s, °C, on the apparent degree of blackness of the fluidized bed. The solid lines are the data obtained by means of the black and white α calorimeters; the dashed lines (drawn through the experimental points) are the data obtained by means of the radiometer. The figures near the curves are $t_{fl.b}$, °C; d = 0.5 mm; w = 1 m/sec.

conditions, the measurement section with dimension of 50 × 50 mm on the side wall was isolated by grooves with a 0.5-mm width and a 4.5-mm depth.

The surfaces of one of the α calorimeters ("black") were given a high degree of blackness (ε_{bl}) by means of a special heat treatment [1], and the surfaces of the other ("white") were covered with a layer of platinum, 50 μm thick, with a low degree of blackness (ε_w), by the plasma deposition method [2]. The values of ε_{bl} and ε_w for surface temperatures of up to 700°C were experimentally determined* by means of a radiation pyrometer [3]. The functions obtained, $\varepsilon_s = f(t_s)$, were extrapolated to higher temperatures as necessary.

The values of the degree of blackness of the oxidized surface of Nichrome (Fig. 1, black points) found experimentally agree quite well with the data from [1] (curve 3). The experimental values of ε_w (open points) lie somewhat higher than the dependence (curve 1) recommended in [4] for polished platinum, which is obviously due to the roughness [5] of the sensor surface.

The heat exchange was studied in equipment with a cross section of 460 × 250 mm, a height of the filled bed of 300 mm, and a distance from the bubble-cap distribution grid to the center of symmetry of the α calorimeter of 150 mm. In one equipment, due to combustion of the natural gas in the fluidized bed, temperatures of 800-1200°C were maintained, and the other bed was fluidized with air at a temperature of 50°C. Particles of white corundum, with a size of d = 0.5 mm, magnesium oxide 0.8-1.2 and 2.5-3.0 mm, and Alundum spheres with a diameter of 5-7 mm were used as the bed material.

The rate of temperature change of the side wall of the α calorimeter was determined over intervals of 50°C, within the limits of which it can be considered as practically constant. For increased accuracy the temperature measurements were recorded by an ÉPP-09M3 potentiometer whose limits of measurement were 0-50°C. Since the temperature difference "bed – body" as a rule exceeds 50°C, the signal from the differential thermocouple was partially compensated by means of a PP-63 potentiometer, used as a controlled voltage source with stepwise switching.

In order to increase the accuracy of the experiments at low surface temperatures, experiments were conducted by a steady-state procedure by means of a water-cooled coil, coated galvanically by means of a layer of nickel with a thickness of ~10 μm; the degree of blackness of this surface, according to the data of [1, 4], was ε_w = 0.05 at a temperature of t_s = 100°C. After the series of experiments with the "white" coil the nickel coating was removed and the coil was subjected to heat treatment, after which according to [1], the degree of blackness of its surface amounted to ε_{bl} = 0.77. The series of experiments was then repeated, but now with the "black" coil.

The radiant and conductive–convective components of the heat-transfer coefficient were calculated by starting from the assumption of their additivity. The system of equations describing complex heat exchange between the fluidized bed and the bodies immersed in it with a different degree of blackness has the form

*The experiments were carried out in the thermophysics laboratory of the All-Union Scientific-Research Institute of Metrology.

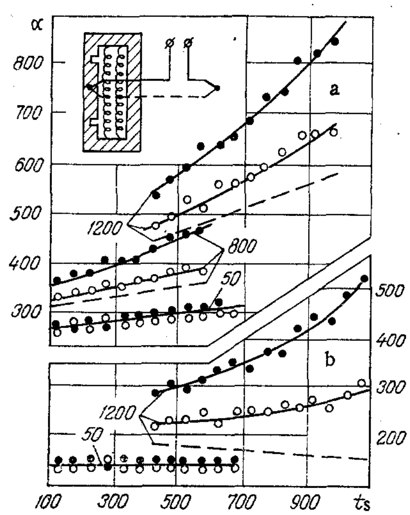

Fig. 3. Dependence of heat-transfer coefficient α, $W/m^2 \cdot deg\ K$, on the surface temperature t_s, °C. The black points are the data obtained by means of the black α calorimeter; the open points, by means of the white α calorimeter. The dashed lines are the calculated values of the conductive–convective heat-exchange components. In the upper left corner is the construction of the α calorimeter. The figures near the curves are $t_{fl.b}$, °C; a) d = 0.5 mm, w = 1 m/sec; b) 5-7 mm; 7.8 m/sec.

$$\alpha_{bl} = \alpha_{cc} + \alpha_{rad.bl} = \alpha_{cc} + \alpha_{rad.o} \Big/ \left(\frac{1}{\varepsilon_{app}} + \frac{1}{\varepsilon_{bl}} - 1 \right), \tag{1}$$

$$\alpha_{w} = \alpha_{cc} + \alpha_{rad.w} = \alpha_{cc} + \alpha_{rad.o} \Big/ \left(\frac{1}{\varepsilon_{app}} + \frac{1}{\varepsilon_{w}} - 1 \right). \tag{2}$$

The radiant heat-transfer coefficient between two blackbodies is determined by the formula

$$\alpha_{rad.o} = \sigma_0 (T_{fl.b}^4 - T_s^4)/(T_{fl.b} - T_s). \tag{3}$$

From the joint solution of Eqs. (1) and (2), neglecting the possible effect on the quantities α_{cc} and ε_{app} of the degree of surface blackness of heat exchange, we obtain the expression for calculating the apparent degree of blackness of the fluidized bed [6], taking into account the geometry of the bed of radiating particles and the effect of cooling of the particles at the heat-exchange surface:

$$\varepsilon_{app} = \left[1 - \frac{1}{2} \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{bl}} \right) + \sqrt{ \frac{1}{4} \left(\frac{1}{\varepsilon_w} - \frac{1}{\varepsilon_{bl}} \right)^2 + \left(\frac{1}{\varepsilon_w} - \frac{1}{\varepsilon_{bl}} \right) \frac{\alpha_{rad.o}}{\alpha_{bl} - \alpha_w} } \right]^{-1}. \tag{4}$$

The apparent degree of blackness was determined also by means of a radiometer with a controlled temperature of the quartz glass by the procedure described in detail in [7, 8]. The values of ε_{app}, obtained by the two independent methods, agree well at high temperatures of the surfaces of the sensors and the quartz glass (Fig. 2). The divergence of the curves at low values of t_s is found to be within the limits of measurement error, as the accuracy of the determination of ε_{app}, by both methods, decreases with decrease of temperature. Later, the values of ε_{app} were used for the calculation by Eqs. (1) and (2) of the radiant and conductive–convective heat-exchange components.

From the data plotted in Fig. 3 for the heat exchange of plates immersed vertically in the fluidized bed (each point is the result of averaging five experiments) it can be seen that the combined heat-transfer coefficient increases with increase of temperature of the bed and surface and also with increase of the surface degree of blackness. The quantity α_{cc} in a bed of fine particles increases linearly with heating up of the plates and more rapidly the higher the bed temperature. This is due to the increase of the conductive heat-exchange component, which is predominant here, because of the increase of thermal conductivity of the fluidizing medium. In a bed of coarse particles, the quantity α_{cc}, on the contrary, decreases somewhat, as the intensity of the convective heat-exchange component, which is predominant in this case, is reduced. For example, if in the formula [9]

$$Nu_{conv} = 0.009\, Ar^{0.5} Pr^{0.33} \tag{5}$$

for the determining temperature we assume $t = 0.5(t_{fl.b} + t_s)$, then the value of α_{conv} decreases by almost 15% with heating up of the body from 100 to 1000°C in a bed with $t_{fl.b}$ = 1200°C.

The difference between the combined heat-transfer coefficient and the value of α_{cc} defines the contribution to the heat exchange of the radiant component. With $t_{fl.b}$ = 50°C the heat-transfer coefficients obtained with the black and white α calorimeters are almost no different from one another. This clearly shows that the intensity of radiation in this case is very low and the combined heat-transfer coefficients are almost equal to α_{cc}. In a high-temperature fluidized bed, the contribution of the radiant component to the heat exchange be-

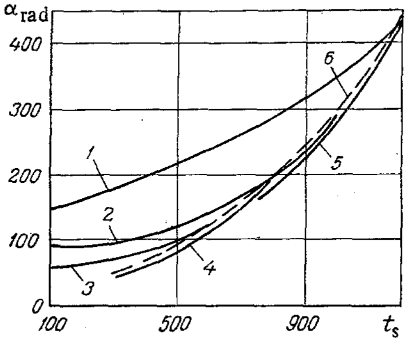

Fig. 4. Dependence of radiant heat-exchange component α_{rad}, W/m^2 · deg K, on the surface temperature t_s, °C (ε_s = 0.8), d = 0.5 mm, w = 1 m/sec; 1, 2, 5) $t_{fl.b}$ = 1200°C; 3, 4) $t_{fl.b}$ = 800°C; 1) calculation without taking account of cooling of particles near the heat-exchange surface; 2, 3) by the method of black and white α calorimeters; 4, 5) by the radiometer method; 6) by the empirical formula (7).

comes significant and even predominant in a bed of coarse particles. The main reason for the increase of the contribution of α_{rad} to the heat exchange with increase of particle diameter is the reduction of the conductive–convective component, while the quantity α_{rad} remains almost identical even in a bed of Alundum spheres of d = 5-7 mm, and in a bed of fine corundum particles of d = 0.5 mm. The authors of [10] also did not detect the effect of the particle diameter (chamotte with d = 0.35–1.25 mm) on the radiant heat-transfer coefficient for $t_{fl.b}$ = 850°C. It follows from this that, on the average, the supercooling of the surface of the particles visible from the side of the sensor is almost identical in a bed of fine and coarse particles, despite the fact that the combined heat-transfer coefficient in the bed of coarse particles is significantly lower. Obviously, here, just as in the bed of very fine (d = 0.043–0.32 mm) particles [11], with increase of d the average time of contact between the particles and the surface of the sensor increases. The whole of a coarse particle cannot be cooled, but only the parts of it close to the cooled surface. With large thermal fluxes, the temperature gradient in a coarse particle will be very considerable.

By the equation

$$\alpha_{rad} = \frac{\sigma_0}{\frac{1}{\varepsilon_{app}} + \frac{1}{\varepsilon_s} - 1} \cdot \frac{T_{fl.b}^4 - T_s^4}{T_{fl.b} - T_s}, \quad (6)$$

using the experimental data for ε_{app}, the heat-transfer coefficients by radiation (Fig. 4, curves 2–5) to a surface (ε_s = 0.8) immersed in a bed of corundum (d = 0.5 mm) have been calculated. The absolute error in determining the quantity α_{rad} does not exceed 24 W/m^2 · deg K. Curve 1 has been plotted without taking account of cooling of the particles near the heat-exchange surface, i.e., when the quantity ε_{app} is equal to the degree of blackness of the free surface of the fluidized bed. The effect of supercooling of the particles near the heat-exchange surface has a significant effect on the quantity α_{rad} in the case of a temperature drop between the bed and the surface of more than 200–300°C, which agrees with the data of [12].

In a bed of magnesium oxide particles the levels of the coefficients α_{rad} are lower than in a bed of corundum. This is completely natural, since the degree of blackness of magnesium oxide is less than for corundum [4] and agrees with the conclusions of [6, 13, and 14] concerning the effect on the radiant heat exchange of the degree of blackness of the bed material.

The dependence of the radiant heat-transfer coefficient on the temperature of the bed for a constant surface temperature (T_s > 800°K) was found to be weak (curves 2, 3 and 4, 5), which is due to cooling of the particles near to the heat-exchange surface.

The special experiments showed that in a high-temperature fluidized bed, the dependence of the combined heat-transfer coefficients on the angle of slope of the plate is almost the same as in the low-temperature fluidized bed (a detailed analysis of the heat exchange of plates in a "cold" bed is given in [15, 16]). The radiant component of the heat-transfer coefficient in this case (with fluidization velocities close to the heat-exchange optimum) varied very weakly (within limits of 10%). It should be noted only that the lowest values of α_{rad} were observed with the horizontal positioning of the sensors above the heat-exchange surface, when the contact time of the particles with the heat-exchange surface increased strongly. For practical calculations of the heat-transfer coefficient by radiation to a surface immersed in a high-temperature fluidized bed of the materials investigated (ε_m = 0.3–0.6), the simple empirical formula

$$\alpha_{rad} = 7{,}3\,\sigma_0 \varepsilon_m \varepsilon_s T_s^3 \quad (7)$$

can be used.

It should be noted that the cubic dependence of α_{rad} on the temperature is theoretically obtained from the Stefan–Boltzmann law for heat exchange by radiation between bodies having an almost identical temperature:

$$\lim \alpha_{\text{rad}}(T_1 \to T_2) = 4\sigma_{\text{sc}} T^3. \tag{8}$$

But in this case the conclusion cannot be drawn from Eq. (7) that the temperatures of the surface and bed of radiating particles are equal, since the experimentally measured radiant thermal flux when calculating α_{rad} is not related to the temperature difference between radiating particles and the surface, as was done in Eq. (8), but to the temperature difference between the core of the fluidized bed (this temperature, in contrast to the temperature of the bed of radiating particles, is easily measured and usually is known for calculations) and the heat-exchange surface.

It can be seen from Fig. 4 that the error in the calculation by the empirical formula (curve 6) for $t_s >$ 850°K does not exceed 10%. With small values of the surface temperature, in the majority of cases the role of radiation in a fludized bed can be neglected.

NOTATION

ε, integrated degree of blackness; t, temperature, °C; T, temperature, °K; α, heat-transfer coefficient, W/m^2 · deg K; d, particle size, mm; w, fluidization velocity, m/sec; σ, coefficient of radiation, W/m^2 · deg K^4; Nu, Nusselt criterion; Ar, Archimedes number; Pr, Prandtl number. Indices: bl, black sensor; w, white sensor; s, heat-exchange surface; fl.b, fluidized bed; app, apparent; rad, radiant; cc, conductive–convective; conv, convective; m, material; sc, scaled; o, corresponds to a black body.

LITERATURE CITED

1. A. G. Blokh, Principles of Heat Exchange by Radiation [in Russian], Gosénergoizdat, Moscow–Leningrad (1962).
2. É. Krechmar, Sputtering of Metals, Ceramics, and Plastics [Russian translation], Mashinostroenie, Moscow (1968).
3. R. Harrison, Radiation Pyrometry [Russian translation], Mir, Moscow (1964).
4. A. E. Sheindlin, Radiative Properties of Solid Materials [in Russian], Énergiya, Moscow (1974).
5. A. S. Nevskii and L. V. Il'chukova, Teplofiz. Vys. Temp., No. 6 (1968).
6. V. S. Pikashov, S. S. Zabrodskii, K. E. Makhorin, and A. I. Il'chenko, in: Heat and Mass Transfer in Dispersed Systems [in Russian], Vol. 5, Nauka i Tekhnika, Minsk (1968).
7. Yu. M. Goldobin, O. M. Panov, and A. P. Baskakov, Dep. in "Informénergo," Journal of Abstracts, All-Union Scientific-Research Institute of Technical Information, Heat and Mass Exchange [in Russian], No. 8 (1976).
8. Yu. M. Goldobin and V. M. Makushenko, in: Industrial Ovens with Fluidized Beds [in Russian], No. 242, Ural Polytechnic Institute, Sverdlovsk (1976).
9. A. P. Baskakov et al., Powder Technol., No. 8 (1973).
10. A. P. Baskakov and Yu. M. Goldobin, Izv. Akad. Nauk SSSR, Energ. Transport, No. 4 (1970).
11. H. S. Mickley et al., Chem. Eng. Prog., Symp. Ser., 57, No. 32 (1961).
12. K. E. Makhorin, V. S. Pikashov, and G. P. Kuchin, Khim. Tekhnol., No. 2 (1976).
13. V. S. Pikashov, S. S. Zabrodskii, K. E. Makhorin, and A. I. Il'chenko, Izv. Akad. Nauk BSSR, Ser. Fiz.-Energ. Nauk, No. 2 (1969).
14. A. I. Il'chenko, V. S. Pikashov, and K. E. Makhorin, Inzh.-Fiz. Zh., 14, No. 4 (1968).
15. A. P. Baskakov and N. F. Filippovskii, Inzh.-Fiz. Zh., 20, No. 1 (1971).
16. N. F. Filippovskii and A. P. Baskakov, Teor. Osn. Khim. Tekhnol., 6, No. 5 (1972).