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CALCULATING RADIANT HEAT EXCHANGE BETWEEN A FLUIDIZED BED AND A SURFACE

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UDC 66.096.5

Radiant heat transfer in a nonisothermal fluidized bed is calculated.

The contribution of radiant heat transfer becomes important in heat exchange between a high-temperature fluidized bed and a surface [1]. The radiant flux is usually calculated using a formula which is valid for two gray isothermal surfaces [2]:

$$q_r = \sigma\varepsilon_{cr}\left[\left(\frac{T_{bc}}{100}\right)^4 - \left(\frac{T_{ss}}{100}\right)^4\right], \tag{1}$$

where

$$\varepsilon_{cr} = \frac{1}{\varepsilon_{ss}} + \frac{1}{\varepsilon_{bc}} - 1.$$

A certain average steady-state temperature profile is formed in the process of heat transfer close to the submerged body. The effect of this profile is taken into account by replacing ε_{bc} with the effective value of the degree of blackness of the fluidized bed [3]:

$$\varepsilon_e = \varepsilon_e(T_{ss}, T_{bc}, \varepsilon_p). \tag{2}$$

There are presently no methods which make it possible, after assigning values to ε_p, T_{ss}, and T_{bc}, to calculate the temperature profile between the surface and the core of the bed, the function ε_e, and radiant flux without resorting to special measurements of the intensity of the radiation from the bed [3].

This article proposes the calculation of these characteristics on the basis of the model described in [4]. The nonisothermal zone of the bed between the surface and the bed core is represented by a set of N parallel translucent isothermal (since the thermal resistance is concentrated mainly in the gas interlayers [1]) planes with reflection coefficients r and transmission factors τ (Fig. 1). The surface submerged in the bed is represented in the model by the 0-th plane, with reflection coefficient r_{ss} and temperature T_{ss}. The bed core is represented by the N + 1-st plane, with the parameters r_{bc}, T_{bc}. It is assumed that the thickness of the bed is sufficiently great so that $\tau_{bc} = 0$. The coefficients r, τ, and r_{bc} were computed for an assigned blackness of the fluidized particles from equations of [4].

As a first approximation, let us examine the simple case whereby energy is transmitted in a system of N translucent planes by radiation alone. Under steady-state conditions, the energy balance equation for the i-th plane will have the form

$$2\,\varepsilon_i\sigma\left(\frac{T_i}{100}\right)^4 = \varepsilon_i\sum_{k=0}^{N+1}(q_{ik}^- + q_{ik}^+)^{\text{inc}}. \tag{3}$$

Having expressed $q_{ik}^{\pm\text{inc}}$ through the characteristics of the model, we can form the following system of equations relative to the temperature T_k:

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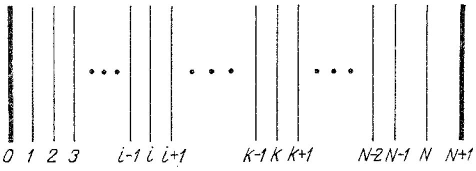

Fig. 1 Model of nonisothermal zone of fluidized bed.

$$\sum_{k=0}^{N}[\delta_{ik}(2-r_{k-1}^{-}a_k^{-}-r_{N-k}^{+}a_k^{+})-E(i-k)(\beta_{ik}^{-}+\beta_{ik}^{+})a_k^{+}-$$
$$-E(k-i)(\gamma_{ik}^{-}+\gamma_{ik}^{+})a_k^{-}]\,\theta_k=\gamma_{i\,N+1}^{-}+\gamma_{i\,N+1}^{+},\; i=1,\;N,$$

where

$$a_k^{+}=\varepsilon_k\left[\frac{1}{1-r_k^{-}r_{N-k}^{+}}+\frac{\tau}{(1-r_{N-k}^{+}r)(1-r_{k-1}^{-}r_{N-k+1}^{+})}\right];$$

$$a_k^{-}=\varepsilon_k\left[\frac{1}{1-r_{k-1}^{-}r_{N-k+1}^{+}}+\frac{\tau}{(1-r_{k-1}^{-}r)(1-r_k^{-}r_{N-k}^{+})}\right];$$

$$\beta_{ik}^{+}=r_{N-i}^{+}\,\frac{\tau_{N-k}(1-r_{N-i}r_{bc})}{\tau_{N-i}(1-r_{N-k}r_{bc})}, \tag{4}$$

$$\beta_{ik}^{-}=\frac{\tau_{N-k}(1-r_{N-i+1}r_{bc})}{\tau_{N-i+1}(1-r_{N-k}r_{bc})},\quad \delta_{ik}=\begin{cases}1, & i=k\\ 0, & i\neq k\end{cases},$$

$$\gamma_{ik}^{+}=\frac{\tau_{k-1}(1-r_i r_{ss})}{\tau_i(1-r_{k-1}r_{ss})},\quad E(i-k)=\begin{cases}1, & i>k\\ 0, & i\leqslant k\end{cases},$$

$$\gamma_{ik}^{-}=r_{i-1}^{-}\,\frac{\tau_{k-1}(1-r_{i-1}r_{ss})}{\tau_{i-1}(1-r_{k-1}r_{ss})},\quad \theta_k=\frac{T_k^4-T_{ss}^4}{T_{bc}^4-T_{ss}^4}.$$

Calculations conducted for different values of ε_p and different distances between particles showed that the temperature profile in the vicinity of the surface is slightly dependent on the properties of the particles forming the bed (at T_{ss} = 300°K and T_{bc} = 1300°K, T_k changes by a maximum of about 10° with a change in ε_p from 0.1 to 0.9) and is determined to a considerable degree by the value of the coefficient r_{ss}.

The radiant flux emanating from the i-th plane consists of the radiation from the i-th plane itself and the radiation reflected by all of the other elements of the system. Having expressed these components through the characteristics r, τ, r_{ss}, and r_{bc}, for an assigned temperature distribution we can write the following expression to find the flux emanating from the i-th plane:

$$q_i^{\pm rad}=\sigma\left\{(T_{ss}/100)^4\sum_{k=0}^{N+1}c_{ik}^{\pm}+\left[\left(\frac{T_{bc}}{100}\right)^4-\left(\frac{T_{ss}}{100}\right)^4\right]\sum_{k=1}^{N+1}c_{ik}^{\pm}\theta_k\right\}, \tag{5}$$

where

$$c_{ik}^{+}=\delta_{ik}a_{ik}^{+}+E(i-k)\,\frac{\beta_{ik}^{+}}{r_{N-i}^{+}}\,a_k^{+}+E(k-i)\,\gamma_{ik}^{+}r_i^{-}a_k^{-};$$

$$c_{ik}^{-}=\delta_{ik}a_k^{-}+E(i-k)\,\beta_{ik}^{-}r_{N-i+1}^{+}a_k^{+}+E(k-i)\,\frac{\gamma_{ik}^{-}}{r_{i-1}^{-}}\,a_k^{-}.$$

The radiant flux emanating from the bed in the direction of the immersed surface is determined by the quantity q_1^{-rad}, calculated in accordance with Eq. (5). In the case of an isothermal system, when $T_k = T_{bc}$ for all k and $\theta_k = 1$ accordingly, the flux emanating from the bed will be equal to $q_{bc} = \varepsilon_{c}r\sigma(T_{bc}/100)^4$. The ratio of the quantity q_1^{-rad} to the flux from the isothermal bed can be used to obtain an expression for the effective radiating power of a nonisothermal fluidized bed

$$\frac{\varepsilon_e}{\varepsilon_{bc}}=A\left(\frac{T_{ss}}{T_{bc}}\right)^4+B, \tag{6}$$

where

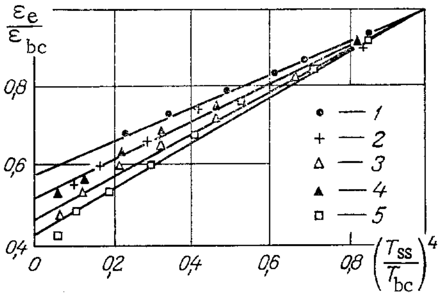

Fig. 2

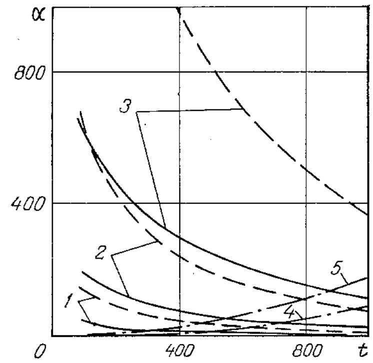

Fig. 3

Fig. 2. The function $(\varepsilon_e/\varepsilon_{bc})[(T_{ss}/T_{bc})^4]$ according to the data in [3]: 1) T_{bc} = 600°C, d_p = 0.32 mm; 2) 800 and 0.32, respectively; 3) 1000 and 0.32; 4) 1000 and 0.5; 5) 1225 and 0.5.

Fig. 3. Temperature dependence of the interphase and radiant heat-transfer coefficients: 1, 2, 3) the function $\alpha_p^*(t_{bc})$ for d_p = 0.5; 1; $2 \cdot 10^{-3}$ m, respectively; the solid curves correspond to W = 2; the dashed lines correspond to W = 5; 4) $\alpha_p^{rad}(T_p, T_p)$; 5) $\alpha_p^{rad}(T_p, 0.5\,T_p)$; α, W/m²·deg C; t, °C.

$$A = (1 - r_{ss} r_1^+) \left[\sum_{k=0}^{N+1} c_{1k}^- (1 - \theta_k) - r_1^+ \varepsilon_{ss} \right] \frac{1}{\varepsilon_{bc}};$$

$$B = (1 - r_{ss} r_1^+) \frac{1}{\varepsilon_{bc}} \sum_{k=1}^{N+1} c_{1k}^- \theta_k .$$

Results are presented in [3] from an experimental study of the dependence of ε_e on (T_{ss}, T_{bc}) for particles of different diameters. Following (6), Fig. 2 shows this data in the coordinates $\varepsilon_e/\varepsilon_{bc}$, $(T_{ss}/T_{bc})^4$. The experimental points are approximated well by straight lines, similar to (6), within the range of surface temperatures $T_{ss} > 0.5\,T_{bc}$, or $t_{ss} > 0.5\,t_{bc} - 136.5$°C. This allows us to suggest that the temperature profile near the surface in the present experiment was formed mainly by radiative heat transfer. The conditions under which radiant transfer comes to have such a significant effect can be determined by comparing the intensities of the two basic mechanisms of heat transfer to the particles – interphase and radiant.

Figure 3 shows the corresponding relations for different particles and conditions. The interphase heat-transfer coefficient was calculated by the method proposed in [3], while the radiant heat-transfer coefficient was calculated for two cases: transmission of energy between particles with temperatures close to one another, and between a particle and a surface with a temperature of $T = 0.5\,T_p$. The formula used to calculate the radiant heat-transfer coefficient:

$$\alpha_p^{rad}(T_p, T) = 0.01\,\sigma\varepsilon_p \left[\left(\frac{T_p}{100} \right)^2 + \left(\frac{T}{100} \right)^2 \right] (T_p + T). \tag{7}$$

It can be seen from Fig. 3 that radiative heat transfer predominates for small particles ($d_p \le 0.5$ mm) at a temperature of ~ 500°C and number of fluidizations $W \le 5$. Only the particles closest to the surface take part in conductive-convective heat transfer, whereas the particles farther removed from the surface also (along with the near-surface particles) participate in radiative heat exchange. All this allows us to suggest that, with the satisfaction of the condition $\alpha_p^{rad} > \alpha_p^*$, radiative heat transfer is substantial even at relatively low temperatures (~ 500°C) and plays the main role in forming the temperature distribution close to the surface. When $\alpha_p^{rad} < \alpha_p^*$, the role of radiative transfer is negligible, the temperature profile is formed mainly by conductive-convective transfer, and the percentage of energy transmitted by radiation is small. The assumption [1, 5, 6] of the additivity of conductive-convective and radiative heat transfer is valid under these conditions; this assumption is the basis for an experimental method of determining the radiative component from the difference between the heat-transfer coefficients of identical transducers with different degrees of blackness [3, 6].

TABLE 1. Estimates of α_{con} and α_r at Different Values of System Parameters (r_{ss} = 0.1 for the numbers without parentheses; r_{ss} = 0.9 for the numbers in parentheses)

	T_{ss}=700 K				T_{ss}=1100 K			
ε_p	α_{con}	α_r	α_Σ	$\frac{\alpha_r}{\alpha_\Sigma}$	α_{con}	α_r	α_Σ	$\frac{\alpha_r}{\alpha_\Sigma}$
	$N=2$				$y_p=1,3$			
0,1	34,7 (75)	64,6 (19,3)	99,3 (94,3)	0,65 (0,2)	38,7 (80,6)	128,3 (32,6)	157 (113,2)	0,82 (0,29)
0,9	48,9 (81,9)	122,4 (22,5)	171,3 (103,4)	0,7 (0,22)	45,1 (91,1)	265 (37,5)	310,1 (128,6)	0,85 (0,29)
	$N=5$				$y_p=2$			
0,1	12,4 (30,5)	73,9 (20,15)	86,3 (50,6)	0,85 (0,4)	9,92 (32,9)	142,4 (33,6)	152,3 (66,5)	0,93 (0,5)
0,9	17,4 (32,8)	125,2 (22,6)	142,6 (55,4)	0,88 (0,4)	15,4 (36,4)	267,9 (37,6)	283,3 (74)	0,94 (0,5)
	$N=20$				$y_p=5$			
0,1	3,6 (8,8)	87,6 (21,1)	91,2 (29,9)	0,96 (0,7)	2,9 (9,6)	156,4 (34,5)	159,3 (44,1)	0,98 (0,78)
0,9	5,2 (9,35)	150,3 (23,4)	155,5 (32,75)	0,97 (0,71)	4,7 (10,5)	289,4 (38,3)	294,1 (48,8)	0,98 (0,78)

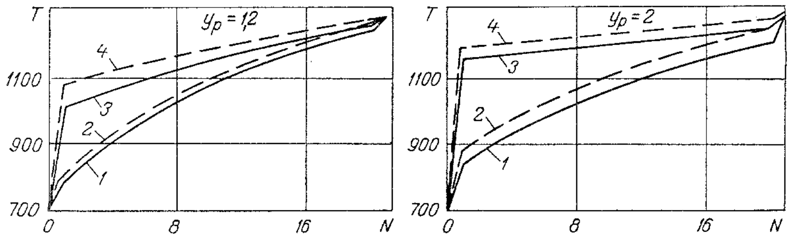

Fig. 4. Temperature profile formed close to a surface immersed in a bed with radiative transfer for the case N = 20: 1) r_{ss} = 0.1, ε_p = 0.1; 2) 0.1 and 0.9, respectively; 3) 0.9 and 0.1; 4) 0.9 and 0.9.

When $\alpha_p^{rad} > \alpha_p^*$, the temperature gradient is also determined to a substantial degree by radiative transfer, and the additivity hypothesis becomes invalid. In this case, certain estimates can be obtained through calculation according to the system of equations (4). Figure 4 shows the temperature profiles formed close to the surface at different particle parameters and bed expansions. It follows from the data in the figure that the temperature gradient near the wall is quite different at r_{ss} = 0.1 and r_{ss} = 0.9. Table 1 shows estimates of radiant and conductive transfer at different surface temperatures for strongly and weakly reflective particles and wall.

It follows from Table 1 that the role of radiation in energy transmission may be very substantial. Here, although α_Σ is greater for a poorly reflecting surface (r_{ss} = 0.1) than for a white wall (r_{ss} = 0.9) and although it increases more rapidly with an increase in T_{ss}, the contribution of radiation is not determined by the difference between the heat-transfer coefficients for a "black" surface and a "white" surface. As can be seen from Table 1 the total heat-transfer coefficient is strongly dependent on the difference between the temperatures T_{ss} and T_{bc}. Thus, with $\alpha_p^{rad} > \alpha_p^*$, the satisfaction of conditions such as a much larger increase in $\alpha_\Sigma(T_{ss})$ for a "black" transducer than for a "white" transducer, or a value of α_Σ for the "black" transducer larger than the value of α_Σ for the "white" transducer, is not evidence of the additivity of the two mechanisms of heat transfer. In this case, the radiative component of heat transfer cannot be determined from the difference $\alpha_\Sigma(r_{ss}=0.1) - \alpha_\Sigma(r_{ss}=0.9)$, similar to [6].

The coefficients A and B in Eq. (6) may be determined from the data in Fig. 2 for the conditions of the experiment in [3]. For the ε_p data and the distances between particles, by solving system (4) we can determine the value of N for which coefficients A and B in (6) will be the same as in the experiment. Such calculations allowed us to obtain the following estimates, which are valid for the conditions of the given experiment:

1) the nonisothermal zone between the surface and the bed core is 5-20 particle rows wide with distinct expansion of the bed;

2) particle cooling near the surface is quite substantial and amounts to 150-400°K for the first row from the wall at T_{ss} = 573°K and T_{bc} = 873-1498°K.

Thus, the results of the calculations and their comparison with experimental results make it possible to more rigorously determine the role of radiation in high-temperature heat exchange and the limits of the applicability of the hypothesis on the additivity of convective and radiative heat transfer.

NOTATION

σ, Stefan–Boltzmann constant; ε, degree of blackness; T, temperature, °K; r, reflection coefficients; τ, transmission factor; r_i, τ_i, reflection coefficients and transmission factors of i translucent planes, respectively; t, temperature, °C; r_i^+, r_i^-, reflection coefficients of i translucent planes and one of the planes bounding the system; q, heat flux, $W/m^2 \cdot deg\ C$; α, heat-transfer coefficient, $W/m^2 \cdot deg\ C$; W, number of fluidizations; α_p^*, interphase heat-transfer coefficient, $W/m^2 \cdot deg\ C$; y_p, distance between particles in d_p; d_p, particle diameter. Superscripts: +, flow in the direction of the bed core; −, flow in the direction of the wall; rad, radiative; inc, incident; subscripts: cr, corrected; e, effective; bc, core of the bed; ss, surface submerged in the bed; p, particles; con, conductive; r, radiant; Σ, total.

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HIGH-TEMPERATURE THERMAL CONDUCTIVITY OF NEON AT TEMPERATURES UP TO 5000°K AND ARGON UP TO 6000°K

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UDC 536.23

We fit the experimental data on the thermal conductivity of neon at temperatures of T = 600-5000°K and of argon for T = 500-6000°K.

In [1] we fitted the experimental data on the thermal conductivity of krypton and xenon at temperatures up to 5000°K and atmospheric pressure, and we showed that, starting from some value of the temperature, the thermal conductivity of these gases can be represented by a power equation with a specified value of the exponent for T. In the present paper we conduct a similar examination of neon and argon.

Neon. The available experimental studies on the thermal conductivity of neon at atmospheric pressure in high temperature ranges are shown in Table 1. It can be seen from Table 1 that up to 2700°K the thermal conductivity of neon has been measured by various methods: for T > 2700°K there are, as yet, only the data of [2], obtained by means of a shock tube.

Figure 1 shows the available experimental data (Table 1) in coordinates of log λ vs log T. It can be seen that in the 600-5000°K range the experimental results lie close to a straight line. This indicates that in this temperature range the thermal conductivity of neon can be described by a power equation with a constant value of the exponent of T.

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