EMISSIVITY OF AN INHOMOGENEOUS FLUIDIZED BED

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We calculate the degree of blackness of the surface of an isothermal inhomogeneous fluidized bed.

In [1-3] we described a model of radiant transfer in a fluidized bed that takes account of the effects of multiple reflection of the radiation by particles. As a result of calculations using this model, it was determined that the region of possible values of the degree of blackness of an isothermal homogeneous bed lies between the curves of $\varepsilon_{fb}(\varepsilon_p)$ for a dense bed (m = 0.4) and a rarefied bed (m ≥ 0.95) for ε_p = 0-1. The $\varepsilon_{fb}(\varepsilon_p)$ curves have no analytic representation, but as it turned out, they can be satisfactorily approximated in the ε_p = 0.01-1 range by the power functions

$$\varepsilon_{fb} = \varepsilon_p^{0.485} \tag{1}$$

for the dense bed and

$$\varepsilon_{fb} = \varepsilon_p^{0.31} \tag{2}$$

for the rarefied bed. The average error of the approximation does not exceed 1% for formula (1) and 0.5% for formula (2).

The direct application of the results obtained is complicated by the fact that the high-temperature bed fluidized by the gas is inhomogeneous. Following [1-3], we can determine only the average values of ε_{fb} for the condition when the time and area of averaging are much larger than the period of phase change in the bed at the surface and the area of its contact with the bubble, respectively. In the present study, therefore, we attempt to determine the emissivity of an isothermal inhomogeneous fluidized bed as a whole and the emulsion phase and bubbles forming it.

To estimate the effect of the structure of the dispersed medium on its emissivity, we shall consider an isothermal inhomogeneous fluidized bed in contact with a heat-exchange surface, part of which is the window of the instrument for measuring the radiation flux (for example, a radiometer [4]) or a specified segment of the heat-exchanger wall. The radiation flux received by the instrument will vary periodically as the emulsion is replaced by the boiling bubbles.

In accordance with the two-phase theory [5], the emulsion phase is a homogeneous fluidized bed whose porosity is close to m_0. Therefore, in order to determine the degree of blackness of its surface, we can use formula (1) directly.

In calculating the radiation flux, we can consider each bubble in the bed independently. This is due to the high optical density of the emulsion separating the bubbles. As was shown in [1], for total absorption of the incident radiation flux it is sufficient to have a dense dispersed layer whose thickness is 5-6 times the particle diameter.

Suppose that in the emulsion phase there moves a bubble of given equivalent diameter D_b at a velocity given, in accordance with [6], by the formula

$$u_b = 0.711\sqrt{gD_b}. \tag{3}$$

We assume that when the bubble approaches the heat-exchange surface, it is deformed into a segment of a sphere (Fig. 1), retaining the same volume and velocity. For a given degree of deformation of the bubble the geometric center of the spherical segment lies at a distance

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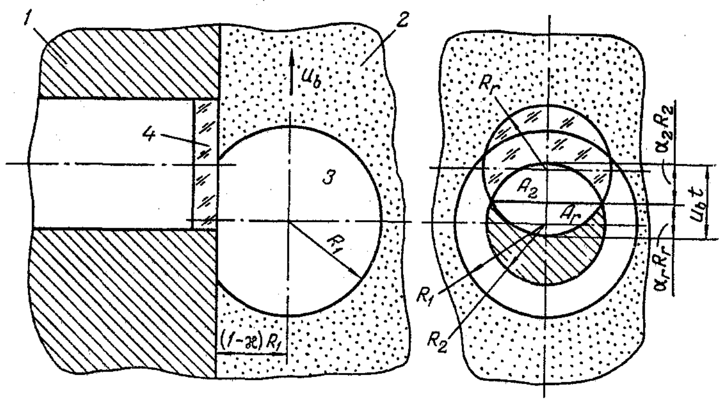

Fig. 1 Model for calculating the radiation of a bubble in a fluidized bed: 1) wall; 2) emulsion phase of the fluidized bed; 3) bubble; 4) radiometer window.

$(1-\varkappa)R_1$ from the surface, and its radius is determined from the condition that the volume remains constant when the bubble is deformed:

$$R_1 = D_b[2(2-\varkappa)^2(1+\varkappa)]^{-1/3}. \quad (4)$$

The radius of the base of the segment is

$$R_2 = R_1\sqrt{\varkappa(2-\varkappa)}. \quad (5)$$

The base of the segment is formed by the window through which the radiation emerges from the bubble, represented in this case as a spherical surface with a degree of blackness ε_{em} (since $D_b \gg D_p$ at all times). For a given bed temperature and a given ε_{em} the density of the radiant flux leaving the bubble cavity corresponds to an effective degree of blackness [7]

$$\varepsilon_b = \frac{2\varepsilon_{em}}{2-(1-\varepsilon_{em})[1+\operatorname{sgn}(1-\varkappa)\sqrt{1-\varkappa(2-\varkappa)}]}. \quad (6)$$

Since ε_b is independent of external factors, the base of the deformed bubble can be regarded as a circle with radius (5) and degree of blackness (6), included in a surface whose emissivity is ε_{em}. The density of the resulting energy flux sensed by the radiometer or by the specified segment of the heat-exchange surface from the directly adjacent fluidized bed will be

$$q_{em} = \sigma\left(\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_{em}}-1\right)^{-1}\left[\left(\frac{T_{fb}}{100}\right)^4-\left(\frac{T_w}{100}\right)^4\right] \quad (7)$$

during the radiant exchange with the emulsion phase and

$$q_b = \sigma\left(\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_b}-1\right)^{-1}\left[\left(\frac{T_{fb}}{100}\right)^4-\left(\frac{T_w}{100}\right)^4\right] \quad (8)$$

when the exchange of radiation with the bubble takes place. Replacing the emulsion phase with the base of the bubble around the specified segment of the surface or the radiometer window leads to a change of the radiation flux in the ratio

$$\frac{q_b}{q_{em}} = \frac{\varepsilon_w+\varepsilon_{em}-\varepsilon_w\varepsilon_{em}}{\varepsilon_w+\varepsilon_b-\varepsilon_w\varepsilon_b}\,\frac{\varepsilon_b}{\varepsilon_{em}}. \quad (9)$$

For the radiometer $q_b/q_{em} = \varepsilon_b/\varepsilon_{em} > 1$, since we always have $\varepsilon_b > \varepsilon_{em}$.

Let us follow the dynamics of the variation of the radiation flux sensed by the radiometer when the bubble passes. As the dimensionless scale of fluctuations in the radiation of the fluidized bed it appears convenient to use the value of the optical contrast between the phases, defined as follows:

$$K = \frac{q_b}{q_{em}} - 1. \quad (10)$$

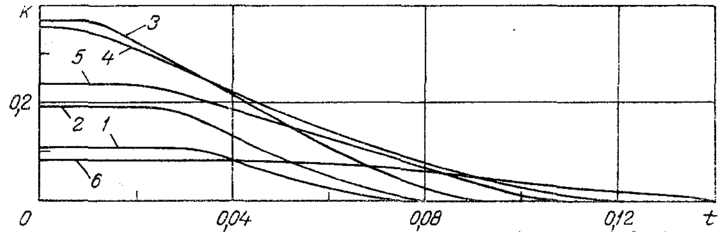

Fig. 2. Recorded phase contrast during the time when the bubble passes by the radiometer window (time counted from the moment of maximum radiation intensity): $D_r = D_b = 0.05$ m; $\varepsilon_w = 1$; $\varepsilon_p = 0.27$; 1) $1-\varkappa = 0.08$; 2) 0.16; 3) 0.4; 4) 0.8; 5) 1.12; 6) 1.6. t, sec.

The entire cycle of phase change around the instrument window can be divided into four time intervals: t_1, contact with the emulsion; t_2, filling of the radiometer window by the bubble; t_3, contact with the bubble; t_4, removal of the bubble from the radiometer window. The duration of the phase-change cycle depends on the bubble tracking frequency. The intervals t_i (i = 2, 3, 4) are determined by the dimensions of the bubble and the value of $\varkappa$. Depending on the ratio of the dimensions of the instrument window to the base of the deformed bubble, there are three possible variants for its passage:

$$1)\ R_2 < R_r\colon\ t_2 = t_4 = D_2/u_b;\ t_3 = (D_r - D_2)/u_b;\quad 2)\ R_2 = R_r\colon\ t_2 = t_4 = D_2/u_b = D_r/u_b;\ t_3 = 0;\quad 3)\ R_2 > R_r\colon\ t_2 = t_4 = D_r/u_b;\ t_3 = (D_2 - D_r)/u_b. \tag{11}$$

The radiation flux density q_r sensed by the radiometer in time interval t_1 is equal to the density of the resulting flux upon radiation exchange with the emulsion and is given by formula (7).

During time interval t_3 the flux q_r is equal to the flux q_b if $R_2 \geq R_r$. In the case when $R_2 < R_r$:

$$q_r = aq_b + (1 - a)\, q_{em}, \tag{12}$$

where $a = (R_2/R_r)^2{}_2$.

During the period of covering (t_2) and uncovering (t_4) of the radiometer window by the bubble, the instrument senses radiation from both phases. We have

$$q_r(t) = a(t)\, q_b + [1 - a(t)]\, q_{em}, \tag{13}$$

where $a(t) = A_b(t)/\pi R_r^2$; $A_b(t)$ is the area of the radiometer window covered by the base of the bubble:

$$A_b(t) = A_2(t) + A_r(t), \tag{14}$$

here $A_i = R_i^2\,[\arcsin\sqrt{2\alpha_i - \alpha_i^2} - (1 - \alpha_i)\sqrt{2\alpha_i - \alpha_i^2}\,]\ (i = 2,\ i = r)$ are the areas of the circular segments forming the zone of contact between the instrument and the bubble when the window is partially covered (see Fig. 1);

$$\alpha_2 = \frac{u_b t\,(D_r - u_b t)}{D_2\,(R_2 + R_r - u_b t)};\quad \alpha_r = \frac{u_b t\,(D_2 - u_b t)}{D_r\,(R_2 + R_r - u_b t)}. \tag{15}$$

Formulas (12)-(15) enable us to determine the instantaneous value of the local radiation flux and the value averaged over the cycle of phase change. Figure 2 shows the results of the calculation of the phase contrast recorded by the radiometer when the bubble passes by. It can be seen from the figure that the maximum value of K is attained for a specific degree of deformation of the bubble which depends on the ratio of D_r to D_b. These parameters, as well as the configuration of the heat exchanger, define the duration of t_2 and t_4 and the nature of the function $q_r(t)$.

Figure 3 shows how the value of maximum phase contrast attained in local radiant heat exchange varies as a function of the degree of blackness of the particles and the specified segment of the heat-exchange surface or the radiation receiver which has various dimensions in relation to the bubble. Since the bubble of deformation was random, the results of the calculation were averaged with respect to the parameter $\varkappa$ in the range $\varkappa$ = 0.8-1.6. As can be seen from the figure, in the experimentally investigated range of values ε_p = 0.2-0.7 the radiation flux emitted by the bubble is about 25% higher, on the average, than the radiation from the emulsion, which agrees with the experimental data of [4].

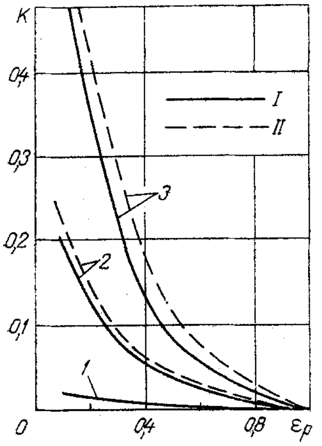

Fig. 3

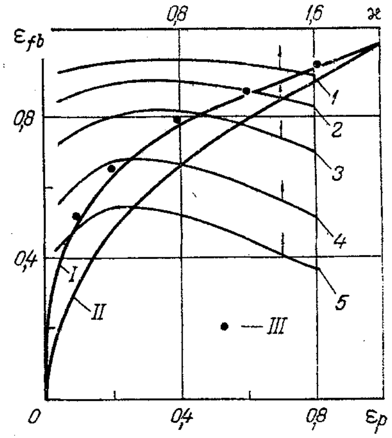

Fig. 4

Fig. 3. Maximum recorded phase contrast as a function of the degree of blackness of the particles and the wall: I) $\varepsilon_w = 0.4$; II) $\varepsilon_w = 1$; 1) $D_r = 2.5\ D_b$; 2) $D_r = D_b$; 3) $D_r = 0.25D_b$.

Fig. 4. Emissivity of a maximum inhomogeneity fluidized bed as a function of the bubble deformation parameter: 1) $\varepsilon_p = 0.8$; 2) 0.6; 3) 0.4; 4) 0.3; 5) 0.1, the functions $\varepsilon_{fb}(\varepsilon_p)$ for the rarefied (I) and dense (II) homogeneous beds and the degree of blackness of the maximum inhomogeneity bed averaged over the parameter $\varkappa$ (III, $D_r = D_b$).

A comparison of the values of recorded phase contrast K for $\varepsilon_w = 1$ for different ratios of the diameters of the instrument window and the bubble enables us to evaluate the spatial resolution of the radiometer. The local measurements of the radiation fluxes will be sufficiently reliable only if $D_r \le D_b$.

Formulas (12)-(15) enable us to calculate the value of the radiation in the case of flux local radiation exchange (with a segment of a large heat-exchange surface or a surface whose dimensions are commensurable with those of the bubble), when the alternation of phases causes oscillations in the radiation flux with rspect to time. In the case of radiation exchange with a very large surface, the inhomogeneity of the fluidized-bed structure leads to a spatial inhomogeneity in the radiation flux. It is found to be possible to determine the exact upper and lower limits of the degree of blackness of the surface of an inhomogeneous fluidized bed. Since $\varepsilon_{fb} \ge \varepsilon_{em}$, the lower limit of the domain of the values of ε_{fb} is determined by formula (1). To find the upper limit, we used the idea of a fluidized bed with a maximum inhomogeneity, i.e., a set of spherical bubbles touching one another in the emulsion phase. The results of the calculation of the degree of blackness of the maximum inhomogeneity bed are shown in Fig. 4. As can be seen from the figure, the values of ε_{fb} averaged over $\varkappa$ for a maximum inhomogeneity fluidized bed practically coincide with the relation (2) for a homogeneous rarefied bed. Consequently, the relations (1) and (2) can be used for determining the boundaries of the region of values of the degree of blackness of the fluidized bed independently of its structure. The degree of blackness of the surface of an inhomogeneous fluidized bed is

$$\varepsilon_{fb}(\varepsilon_p) = \frac{f}{f^*}\,\varepsilon_p^{0.31} + \left(1 - \frac{f}{f^*}\right)\varepsilon_p^{0.485}, \tag{16}$$

where $f^* = 0.614$ is the fraction (averaged over the deformation parameter κ) of the heat-exchange surface in contact with the bubbles in the maximum inhomogeneity bed, for the cubic packing of the bubbles that is assumed in the calculation. The value of f can be calculated from the formula [3]

$$f = 1.56\frac{\mathrm{Re} - \mathrm{Re}_0}{\sqrt{\mathrm{Ar}}}, \tag{17}$$

where $\mathrm{Re} = \dfrac{u_g D_p}{\nu}$; $\mathrm{Ar} = \dfrac{gD_p^3}{\nu^2}\dfrac{\rho_p - \rho_g}{\rho_g}$.

Formula [17] enables us to calculate the average value of the degree of blackness of an inhomogeneous bed adjacent to a surface whose area is much larger than the area of the base of the deformed bubble.

NOTATION

A, surface area; D, diameter; f, fraction of the surface that is in contact with the bubbles; g, acceleration of gravity; k, optical contrast of the phase; m, porosity; q, radiant flux density; R, radius; T, absolute temperature; t, time, u, velocity; ε, degree of blackness; $\varkappa$, degree of bubble deformation, ν, kinematic viscosity; σ, Stefan–Boltzmann constant; Re, Reynolds number; Ar, Archimedes number. Subscripts: 0, start of fluidization; b, bubble; em, emulsion phase; fb, fluidized bed; g, gas; p, particle; r, radiometer; w, wall.

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RADIATIVE–CONDUCTIVE HEAT TRANSFER IN "HEATER–MULTILAYER STRUCTURE" SYSTEM

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The coupled problem of radiative–conductive heat transfer is solved by a numerical method. The integral equation describing radiative heat transfer is approximated with a system of linear algebraic equations.

The main purposes of a thermal experiment are identifying the structure of the mathematical models of the thermal state and analyzing heat-transfer processes which actually occur in objects under study. Natural heating tests are extremely complicated and costly. For this reason, wide acceptance have received testing methods based on studying the thermal state of a natural structure on simulating test stands such as, for instance, test stands simulating radiative heating. Performing such tests requres careful preparation and, above all, scientifically substantiated rational planning. Lately new approaches are taken in many places not only to processing of experimental data but also to optimal organizing of experiments. One way to improve the effectiveness of experimental studies is applying modern methods of mathematical simulation of the thermal state of an object under test stand conditions during the test preparation stage.

In this study will be developed a mathematical model of heating of an axisymmetric structure during tests performed in radiative heating stand, a model based on the solution to the coupled problem of radiative–conductive heat transfer.

The mathematical model of radiative–conductive heat transfer involves a simultaneous solution of two problems, radiative heat transfer in a "heater–irradiated surface" system and transient heat transfer in a multilayer structure.

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