CALCULATION OF EMITTANCE OF A DISPERSE SYSTEM

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The emittance of a disperse system is calculated under the assumption that the particles forming the system have a diffuse gray surface. The calculated results are compared with experiment.

Radiation heat transfer is important in high-temperature (1000°C and above) disperse systems. In order to calculate the radiant flux it is necessary to know the emissivity of the surfaces taking part in the heat exchange — in the present case the emissivity of the surface of a fluidized bed.

Experiments [1-6] have shown that the emittance of a dispersion medium depends mainly on the emissivity of the particles forming the system. By using the methods presented in [7,8] for calculating emittance, the emissivity of the surface of a fluidized bed can be estimated. The appreciable difference between the calculated and experimental results can be accounted for by the fact that these methods do not take account of the interaction of the particles (multiple reflections of radiation from particles), which is important in a concentrated dispersion medium.

In the present article the emissivity of the surface of a concentrated dispersion medium is calculated by taking account of multiple reflection of radiation from the particles and using the following assumptions and model of the system:

1) the particles are spherical and opaque with a diffuse gray surface with emissivity ε_p;

2) the medium in which the particles are dispersed is transparent;

3) the actual disordered disperse system is represented as an assembly of parallel planes, each of which has particles at the nodes of a square net.

Henceforth, the pitch of the net (the distance between centers of neighboring particles) is a parameter of the calculation, and is varied from 1-10 particle diameters.

Since a concentrated disperse system is considered in the present article, the concepts of geometrical optics are used in the calculation [9].

The model is composed of gray particles, and, according to Kirchhoff's law [9], the emissivity of the disperse system is equal to its absorptivity. Therefore the interaction of the system with external radiation is investigated, and the self-radiation of the particles is assumed equal to zero. This procedure is possible for an isothermal system [8,9].

As has been pointed out, a disperse system is considered as an assembly of plane models. The external radiation incident on such a plane formed by a regular arrangement of spheres is partly reflected, partly absorbed, and partly transmitted. If the characteristics of this plane r_t, τ_t, and ε_t are known, the reflection and transmission coefficients of a stack of n planes can be calculated by using the recurrence formulas [10]

$$r_n = r_{n-1} + \frac{\tau_{n-1}^2 r_t}{1 - r_{n-1} r_t}, \quad \tau_n = \frac{\tau_{n-1}\tau_t}{1 - r_{n-1} r_t}. \tag{1}$$

By going to the limit $n \to \infty$, the absorptance of an infinite medium, and consequently the emissivity of its surface ($\lim \tau_n = 0$, $r_n \to R_m$, $\varepsilon_n \to \varepsilon_m$, $R_m + \varepsilon_m = 1$), can be determined.

The values of r_t, τ_t, and ε_t are determined by using the auxiliary scheme shown in Fig. 1, which consists of two ideal black planes 1 and 3 and a two-dimensional model of a dispersion medium 2. A radiation flux with a surface density q_b is specified on plane 1. However,

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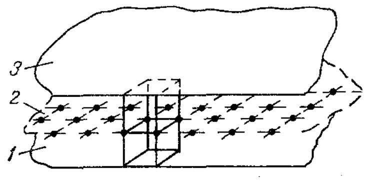

Fig. 1

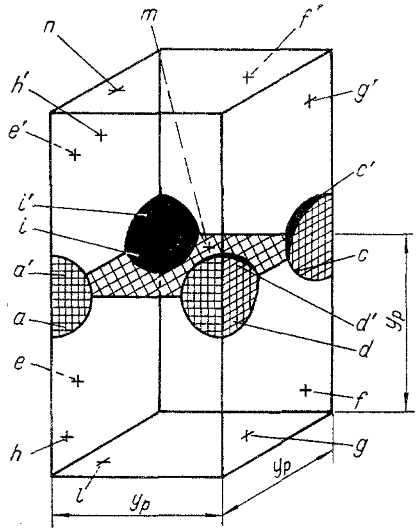

Fig. 2

Fig. 1. Schematic diagram of an infinite two-dimensional model of a dispersion medium.

Fig. 2. Finite model of a dispersion medium.

such a scheme is still too complicated, since it is necessary to take account of the interaction of a large number of particles. The scheme is further simplified by changing from infinite planes to a finite model (Fig. 2). Figure 2 shows a cell formed by elements of black planes 1 and 3 (faces l and n), elements of spheres (a, a', c, c', d, d', i, i') and closed by an auxiliary system of black faces (e, f, g, h, e', f', g', h'). The transfer of radiation between infinite planes does not depend on the distance between them [8]. For convenience it is assumed equal to the distance between centers of neighboring particles y_p. Quadrants of spherical particles of unit radius are placed at the vertices common to the two cubes into which the cell can be divided. A radiation flux of density q_b is specified on the faces e, f, g, h, l of the lower cube. In addition, radiation fluxes of densities q_{bs} and q'_{bs} are specified on the lateral faces (e, f, g, h) of the lower cube and (e', f', g', h') of the upper cube, respectively. These fluxes result from the reflection of radiation from the surfaces of all the remaining particles of the two-dimensional disperse model which are not in the cell. Through face m, which is common to the upper and lower cubes, there pass a radiation flux with a density $q_{bm} + \delta_m$ from the upper cube into the lower and a flux with a density $q'_{bm} + \delta'_m + q''_{bm}$ from the lower cube into the upper. On the surfaces of the octants of the spheres a', i', c', d' belonging to the upper cube, and a, i, c, d belonging to the lower cube the radiation flux densities are written in the form $q'_p + \delta'_p$ and $q_p + \delta_p$ respectively. Here the components of the fluxes q_{bm}, q'_{bm}, q''_{bm}, q_p, and q'_p result from the transformation in the cell of the given flux q_b, and the components δ_m, δ'_m, δ_p, and δ'_p from the transformation of the fluxes q_{bs} and q'_{bs}. After all the fluxes are determined in terms of the given flux q_b, the reflection, transmission, and absorption coefficients of the two-dimensional model can be calculated.

The transfer of radiation in the cell is calculated from the system of equations given in [9]. The solution of this system requires knowing the dimensions and emittances of the surfaces forming the system, and the angular coefficients. The abbreviated notations for the angular coefficients shown in Table 1 are used from now on. Some of the angular coefficients were calculated numerically by the cubature formulas given in [11] and by the three-term interpolation formula [12] with an error of less than 1%. The remaining were found by using the algebra of the angular coefficients [9].

The propagation of the radiation flux q_b in the cell is described by the equations

$$a_1 q'_p - 3r_p CC_r q_p = 2r_p LCq_b, \qquad (2)$$
$$-3r_p CC_r q'_p + a_1 q_p = a_2 r_p q_b,$$

where

$$a_1 = 1 - r_p(2P + Q); \; a_2 = T + 2(G + H).$$

TABLE 1. Notations for the Angular Coefficients $\varphi_{\alpha-\beta}$ for Various Elements of the Model in Fig. 2

α	β: a	i	c	d	e	f	g	h	l	m
a		P	Q	P	H	G	G	H	T	C
i	P		P	Q	H	H	G	G	T	C
c	Q	P		P	G	H	H	G	T	C
d	P	Q	P		G	G	H	H	T	C
e						Y	Z	Y	K	
f					Y		Y	Z	K	
g					Z	Y		Y	K	
h					Y	Z	Y		K	
m	C_r	C_r	C_r	C_r						

After solving Eqs. (2), the components of the fluxes at the surfaces of the cell resulting from the scattering of the flux q_b can be written in the form

$$q_p = a_3 q_b\,,\; q_p' = a_5 q_b\,,\; q_{bm} = 4C_r a_5 q_b\,,\; q_{bm}' = 4Lq_b\,,\; q_{bm}'' = 4C_r a_3 q_b\,, \tag{3}$$

where

$$a_3 = r_p\,\frac{a_1 a_2 + 6r_p LC^2 C_r}{a_1^2 - (3r_p CC_r)^2}\,;$$

$$a_4 = L + \frac{3}{2}\,C_r a_3;\; a_5 = \frac{2r_p C}{a_1}\,a_4.$$

Now it is necessary to calculate the components of the fluxes produced by radiation reflected from particles outside the cell. The quantities q_{bs} and q_{bs}' are not determined, but they can be related to the required components of the flux. The cell under consideration is separated from an infinite set of cells forming the scheme shown in Fig. 1, and must be identical with all the others. Therefore, the energy flux incident on any lateral face of the upper (lower) cube as a result of reflection from the surfaces of particles of the cell must be the same as that from the outside which results from the scattering from particles. Hence for any lateral face of the upper (lower) cube

$$\begin{Bmatrix} q_{bs} \\ q_{bs}' \end{Bmatrix} = a_6 \begin{Bmatrix} q_p + \delta_p \\ q_p' + \delta_p' \end{Bmatrix} + a_7 \begin{Bmatrix} 3Lq_{bs}' + 2C_r(q_p' + \delta_p') \\ 3Lq_{bs} + 2C_r(q_p + \delta_p) \end{Bmatrix}, \tag{4}$$

where $S_p = \pi/2$ is the area of an octant of a unit sphere;

$$S_b = 4y_p^2 - \frac{\pi}{2}\,;\; S_m = 4y_p^2 - \pi;\; a_6 = 2\,\frac{S_p(G+H)}{S_b(1-2Y-Z)}\,;$$

$$a_7 = \frac{S_m L}{S_b(1-2Y-Z)}\,.$$

Now by taking account of these relations the following system of equations can be written for the still unknown components:

$$a_1\delta_p' = 2(G+H)\,r_p q_{bs}' + r_p C(2Lq_{bs} + 3C_r\delta_p);\; q_{bs}' = a_6(q_p' + \delta_p') + a_7[3Lq_{bs} + 2C_r(q_p + \delta_p)], \tag{5}$$
$$\delta_m' = 4(Lq_{bs} + C_r\delta_p),\; a_1\delta_p = 2(G+H)\,r_p q_{bs} +$$
$$+ r_p C(2Lq_{bs}' + 3C_r\delta_p'),\; q_{bs} = a_6(q_p + \delta_p) + a_7[3Lq_{bs} + 2C_r(q_p + \delta_p)],\; \delta_m = 4[Lq_{bs}' + C_r\delta_p'].$$

By using Eqs. (5) and (3) all the components of the fluxes in a cell can be expressed in terms of the external radiation flux density q_b. Then the reflected, transmitted, and absorbed fluxes are found from the following formulas:

$$Q_{ref} = 4TS_p(q_p + \delta_p) + 4KS_b q_{bs} + S_m[(M + 2L + C_r)\,q_{bm} + M\delta_m + 4L(L + 2C_r)\,q_{bs}' + 4C_r(2L + C_r)\,\delta_p'], \tag{6}$$
$$Q_{trans} = S_m\{[4L(4L + M) + M]\,q_b + M\delta_m' + (M + 2L + C_r)\,q_{bm}'' +$$
$$+ 2C_r q_{bm}' + 4L(L + 2C_r)\,q_{bs} + 4C_r(2L + C_r)\,\delta_p\} + 4S_b K q_{bs} + 4S_p T(q_p' + \delta_p'),$$

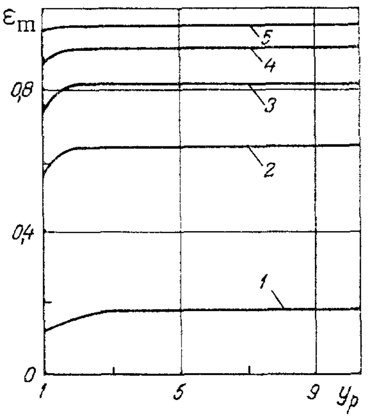

Fig. 3

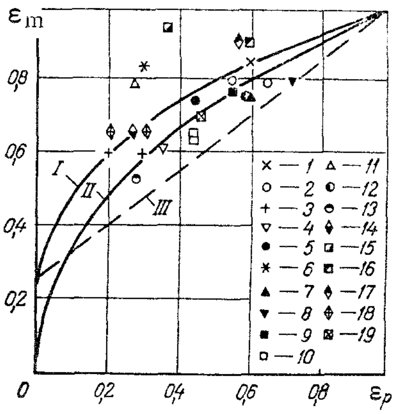

Fig. 4

Fig. 3. Dependence of emissivity of surface of a dispersion medium on distance between centers of particles forming the medium for various values of ε_p: 1) 0.01; 2) 0.25; 3) 0.5; 4) 0.75; 5) 0.95.

Fig. 4. Dependence of emissivity of surface of a fluidized bed on emissivity of particle surface ε_p: I) $y_p = 9.5$; II) $y_p = 1$; III) calculated from Eqs. of [6]. Experimental points: 1-4 [1]; 5-10 [2]; 11, 12 [3]; 13 [4]; 14-17 [5]; 18, 19 [6]; 1, 7, 16) sand; 2, 9, 12, 17) chamotte; 3, 15, 18) ZrO_2; 4, 5, 10, 11, 13, 14) clean corundum; 6) magnesite; 8) blackened corundum; 19) material with a high alumina content.

$$Q_{\mathrm{abs}} = 4\varepsilon_p S_p \Big\{(a_2 + CL)\, q_b + 2\,(G + H + CL)\,(q_{bs} + q'_{bs}) + $$
$$+ (2P + Q)\,(q_p + q'_p) + (2P + Q + 3CC_r)\,(\delta_p + \delta'_p) + \frac{3}{4}\, C\,(q_{bm} + q''_{bm})\Big\}.$$

The total external flux entering the cell and incident on the model (surfaces a, i, c, d, m) can be written in the form

$$Q_{\mathrm{in}} = [4S_p a_2 + (4L + M)\, S_m]\, q_b. \tag{7}$$

Now the reflection, transmission, and absorption coefficients of the two-dimensional model of a dispersion medium can be found as the ratios of the corresponding fluxes to the incident flux:

$$r_t = \frac{Q_{\mathrm{ref}}}{Q_{\mathrm{in}}},\quad \tau_t = \frac{Q_{\mathrm{trans}}}{Q_{\mathrm{in}}},\quad \varepsilon_t = \frac{Q_{\mathrm{abs}}}{Q_{\mathrm{in}}}. \tag{8}$$

As the distance between particles is increased, the reflection and absorption coefficients of the model decrease, and as $y_p \to \infty$ the following relations hold:

$$\lim r_t = 0,\ \lim \varepsilon_t = 0,\ \lim \tau_t = 1. \tag{9}$$

The results of calculations performed for various values of the emissivity of the particle surface (ε_p = 0.01-0.99) and the distance between particles (y_p = 1.01-9.5) are shown in Figs. 3 and 4. The experimental results reported in [6] verify that the emittance of a disperse system is independent of the distance between particle centers as the bed is increased in thickness, and confirm the assumption of the structure of a disperse system used in the solution. Figure 4 shows the calculated dependence of ε_m on ε_p and the results of measurements of the emissivity of a fluidized bed reported in [1-6]. As can be seen from Fig. 4, the calculated and experimental data are in good agreement, with an average deviation of 10% and a maximum of 25%. From the results of the calculation the emittance of a disperse system can be determined from the known emissivity of the particles forming it.

NOTATION

ε_p, emissivity of particle surface; r_p, reflection coefficient for particle surface; y_p, distance between particle centers in model; r_t, τ_t, ε_t, reflection, transmission, and absorption coefficients of two-dimensional model of a dispersion medium respectively; τ_n, r_n, transmission and reflection coefficients of a stack of n identical planes; ε_m, R_m, emissivity and reflection coefficient of surface of disperse system; q_b, q'_{bs}, q'_p, q'_{bm}, q''_{bm}, δ'_p, δ'_m, surface densities of radiation fluxes in cell; $\varphi_{\alpha-\beta}$, angular coefficients; a_1–a_7, coefficients used in solving system (5); S_m, S_b, areas of faces m and e, f, g, h, e', f', g', h' of cell respectively; Q_{ref}, Q_{abs}, Q_{trans}, Q_{in}, reflected, absorbed, transmitted, and incident radiation fluxes.

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POROUS MIXERS FOR GASDYNAMIC LASERS WITH SELECTIVE THERMAL EXCITATION

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Results of experimental studies are presented pertaining to the characteristics of a gasdynamic laser with selective thermal excitation and with the mixing device made of porous material.

Several interesting new methods of mixing the streams in gasdynamic lasers with selective thermal excitation have been proposed in recent years [1-3]. In the first study [1] nitrogen from air was mixed with CO_2 aerosol, in the second study [2] the "subcritical" mode of adding the radiating component to the mixture was considered, and in the third study [3] designs of mixers for adding it to a supersonic supporting stream were developed. Although many designs already exist, it is now still difficult to decide on the final choice of mixer

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