RADIATIVE HEAT TRANSFER IN A CHARGE OF DISPERSE MATERIAL

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An equation for calculating the energy flux created by thermal radiation in disperse charges is derived. The equation describes a one-dimensional process, and correlates well with experimental data.

The problem of the role of radiation in the over-all heat transfer of disperse systems is the most complex and least studied among radiation problems. In most cases, the study of radiative heat transfer through charges of disperse material makes it necessary to take into account the absorption, scattering, and radiation of the particle surfaces, as well as the heterogeneous structure of the charge.

In order that this complex problem lend itself to mathematical treatment, certain simplifications must be made.

Let us examine steady-state heat transfer in an ordered charge situated in a vacuum and consisting of identical spherules having a gray surface (Fig. 1).

The resulting energy flux, created by thermal radiation, was calculated with the aid of two thermal radiation fluxes—J and K—which pass through the charge from opposite directions:

$$q = J - K. \tag{1}$$

This method of dividing the radiation field in a layer into two radiant fluxes propagating in opposite directions has been used by numerous investigators in theoretical computations of radiative transfer [1–3].

According to [3] we have:

$$J_n = BJ_{n-1} + \varepsilon_m(1-B)\sigma T_n^4 + K_n(1-B)(1-\varepsilon_m), \tag{2}$$

$$K_n = BK_{n+1} + \varepsilon_m(1-B)\sigma T_n^4 + J_n(1-B)(1-\varepsilon_m), \tag{3}$$

where B is the transmission coefficient of a layer of disperse material.

We simplified Eqs. (2) and (3) by assuming that the pores in the disperse material layer have the form of a cylinder whose length l is equal to the particle diameter. Let us determine this pore radius R.

Since the number of particles and pores in 1 m^3 of the layer is

$$\frac{6(1-m)}{\pi d^3}, \tag{4}$$

the volume of a pore is

$$\frac{\pi d^3 m}{6(1-m)} = \pi R^2 d, \tag{5}$$

and hence

$$R = 0.41\, d \sqrt{\frac{m}{1-m}}. \tag{6}$$

The amount of heat emitted from a cylindrical pore into the ambient medium is determined from a formula proposed by Sparrow and Eckert [4]:

$$Q = \pi R^2 \varepsilon_p \sigma T^4. \tag{7}$$

The values for ε_p are given by the authors [4] in the form of graphs and tables for an $l/2R$ ratio varying from 0.25 to 4.

From Eq. (7), we have

$$q_p = \varepsilon_p \sigma T^4. \tag{8}$$

It should be noted that, inasmuch as the maximum contribution comes from the bottom of a cylindrical pore, it is important to know exactly the temperature of the bottom, whereas the accuracy of the determination of the wall temperature is less important. Since J_{n-1} and K_{n+1} is the specific heat flux of the pore, while for a layer of disperse material with cylindrical pores B = m, Eq. (1) with consideration of Eqs. (2), (3), and (8), takes the form

$$q = J_n - K_n = \frac{m\varepsilon_p\sigma T_1^4 + (1-m)\varepsilon_m\sigma T_2^4 - m\varepsilon_p\sigma T_4^4 - (1-m)\varepsilon_m\sigma T_3^4}{1+(1-m)(1-\varepsilon_m)} =$$

$$= [m\varepsilon_p\sigma(T_1-T_4)(T_1+T_4)(T_1^2+T_4^2) + (1-m)\varepsilon_m\sigma(T_2-T_3)(T_2+T_3)(T_2^2+T_3^2)] \times [1+(1-m)(1-\varepsilon_m)]^{-1} \tag{9}$$

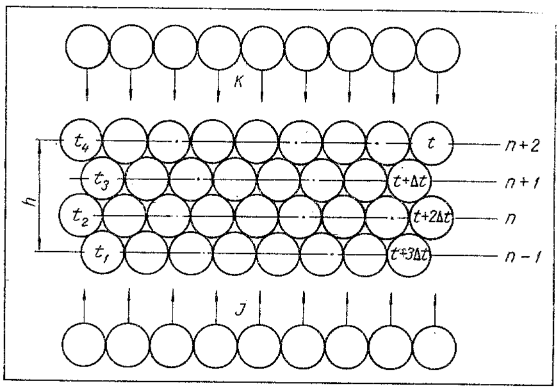

Fig. 1. Model of a charge of granular material.

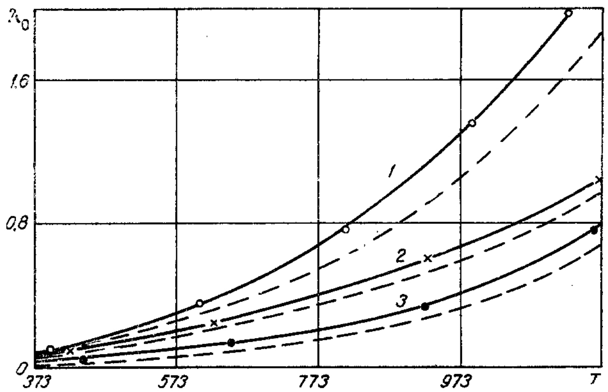

Fig. 2. Temperature dependence of the effective thermal conductivity coefficient of charges of disperse material for a vacuum of 1×10^{-4} mm Hg (the dashed curves correspond to computations from Eq. (14)): 1) pig iron spherules, fraction 3.0 to 4.0 mm, 2) slag spherules, fraction 2.0 to 3.0 mm, 3) pig iron spherules, fraction 0.5 to 1.0 mm.

In [5], it is shown that at relatively small temperature differences $(t_1 - t_2)/t_2 \le 0.2$, the error involved in using $4t_{av}^3$ instead of $(t_1^2 + t_2^2)(t_1 + t_2)$ does not exceed 1%. Then, instead of Eq. (9), we have

$$q = \frac{4T_{av}^3 \varepsilon_p m \sigma (T_1 - T_4) + 4T_{av}^3 \varepsilon_m \sigma (1 - m)(T_2 - T_3)}{1 + (1 - m)(1 - \varepsilon_m)}. \quad (10)$$

On the other hand, we have

$$q = \lambda_r \frac{\Delta t}{\Delta x} = \lambda_r \frac{T_1 - T_4}{h}. \quad (11)$$

From Eqs. (10) and (11), we get

$$\lambda_p = \frac{4T_{av}^3 \sigma h \left[m \varepsilon_p + \left(\frac{T_2 - T_3}{T_1 - T_4}\right)(1 - m)\varepsilon_m \right]}{1 + (1 - m)(1 - \varepsilon_m)}. \quad (12)$$

For a linear temperature distribution in the layer, the quantity $(T_2 - T_3)/(T_1 - T_4)$ is equal to 1/3, while h can be determined from formula

$$h = \frac{nbd}{4}, \quad (13)$$

where b is a coefficient depending on the packing of the particles, which for a dense tetrahedral packing is equal to $2\sqrt{3}$ [9].

Then, with account for Eq. (13), Eq. (12) can be written in the form

$$\lambda_r = \frac{3.46\sigma T_{av}^3 d\,[3m\varepsilon_{\text{п}} + (1 - m)\varepsilon_m]}{1 + (1 - m)(1 - \varepsilon_m)}. \quad (14)$$

Equation (14) was checked qualitatively, by means of the experimental data from [7, 8]. Figures 2 and 3 show the results of this comparison. It should be noted that the analytical curves in Fig. 2 were plotted with the values for the contact thermal conductivity λ_c from [7], while the values for ε_m were taken from [6].

The analytical curve in Fig. 3 was plotted with the aid of λ_t values calculated from a formula proposed in [8]:

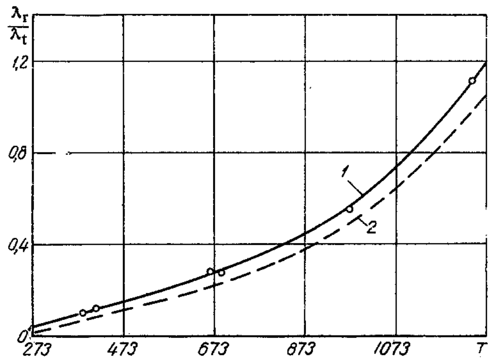

Fig. 3. Temperature dependence of the radiative thermal conductivity coefficient of aluminum spherules: 1) 3.8 mm in diameter [7]; 2) computed from Eq. (14).

$$\lambda_g = \lambda_g \left[1 + 3.91\, \lambda_g^{0.1} (1 - m) \ln \frac{\lambda_m}{\lambda_g} \right]. \quad (15)$$

The good agreement between the theoretical and experimental results indicates that the assumptions made in the model described are permissible and that Eq. (14) is suitable for determining the radiative component of the thermal conductivity of a layer of granular material.

NOTATION

d is the particle diameter, in m; h is the charge thickness, in m; l is the length of a cylindrical pore, in m; m is the porosity; n is the number of particles in a layer of height h; q is the specific heat flux, in W/m^2; R is the radius of a cylindrical pore, in m; T is the absolute temperature, in °K; ε_p, ε_m are the emissivities of a pore and of particle material, respectively; λ_m, λ_g are the thermal conductivity of the particle material and the gas, respectively, in W/m/deg; λ_0 is the effective thermal conductivity coefficient of a charge of disperse material in a vacuum, in W/m/deg; λ_r is the averaged coefficient of effective radiative thermal conductivity, in W/m/deg; λ_t is the component of the coefficient of effective thermal conductivity of disperse material, resulting from the thermal conductivities of the gas and particle material; σ is the Stefan-Boltzmann constant, in W/m^2/°K^4.

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