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A MODEL FOR CALCULATING THE ATTENUATION FACTOR OF A MULTICOMPONENT MEDIUM

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A model and procedure are presented for calculating the attenuation factor of a multicomponent medium, taking account of the size distribution of particles and pores.

The attenuation factor is one of a number of important parameters of materials which are semitransparent to thermal radiation needed to estimate the radiation component of heat transfer, and to solve the radiation — conduction heat-transfer equation. When the attenuation factor is known, radiation heat transfer in an optically thick layer of a heterogeneous medium can be estimated from the Rosseland formula [1]. Expressions are given in [1-4] and in other places for the attenuation factor of a two-component medium with identically sized particles.

In the present paper we propose a model for calculating the attenuation factor of two-component and multicomponent media which takes account of the size distribution of particles and pores.

To explain the proposed procedure, we consider in more detail the simplest model of a two-phase medium consisting of a regular chain of particles (plates) of the first phase of identical size d with the particles of the second phase in between. We choose a segment of arbitrary length L in the medium and consider the attenuation of radiation with an initial intensity I_0 in penetrating this segment. The attenuation occurs both because of true absorption and because of reflection from the phase boundaries. We assume that the reflection is specular and obeys the Fresnel formulas.

Suppose there are N particles of the first phase in the segment L. Then the number of reflections from them is 2N, and the total length of particles of the first phase is h = Nd. In this case

$$I = I_0 (1 - R)^{2N} \exp(-\alpha_1 h) \exp[-\alpha_2 (L - h)], \tag{1}$$

where α_1 and α_2 are the absorption coefficients of the first and second phases, respectively.

Introducing the effective attenuation factor K_e

$$I = I_0 \exp(-K_e L), \tag{2}$$

equating the right-hand sides of Eqs. (1) and (2), and using the fact that $R \ll 1$, we obtain

$$K_e = \alpha_2 + (\alpha_1 - \alpha_2) C + 2 \frac{C}{d} R, \tag{3}$$

where C = h/L = Nd/L is the concentration of particles of the first phase.

If $\alpha_2 = 0$, i.e., the second phase consists of pores, C = 1 − p, where p is the porosity,

$$K_e = (1 - p)(\alpha_1 + 2R/d). \tag{4}$$

This relation is given in [5].

Three-Phase System. The particle sizes are identical and the third phase occupies the spaces between phases 1 and 2, e.g., a glassy phase in which there are crystalline precipitates,

$$K_e = \frac{2R_1}{d_1} C_1 + \frac{2R_2}{d_2} C_2 + \alpha_3 + (\alpha_1 - \alpha_3) C_1 + (\alpha_2 - \alpha_3) C_2. \tag{5}$$

n-Phase System. The particle sizes in each phase are identical, and the n-th phase occupies the spaces between the remaining phases,

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$$K_e = \sum_{i=1}^{n-1} \frac{2R_i}{d_i} C_i + \alpha_n + \sum_{i=1}^{n-1} (\alpha_i - \alpha_n) C_i. \tag{6}$$

In most cases the sizes of particles and pores of heterogeneous materials are different. The distribution function can be determined by microscopic methods, by mercury porosimetry, or by other means.

Two-Phase System. There is a discrete and a continuous distribution of particle sizes.

Suppose there is a distribution of particle sizes within each phase, with the first phase consisting of m different kinds of particles with sizes $d_1, \ldots, d_m$ and concentrations $C_1, \ldots, C_m$. In this case

$$C_i = \frac{N_i d_i}{L}; \quad h = \sum_{i=1}^{m} N_i d_i; \quad \frac{h}{L} = \sum_{i=1}^{m} C_i,$$

and by analogy with the derivation of Eq. (3) we obtain

$$K_e = \alpha_2 + (\alpha_1 - \alpha_2) \sum_{i=1}^{m} C_i + 2R \sum_{i=1}^{m} \frac{C_i}{d_i}. \tag{7}$$

If the first phase consists of pores, $\alpha_1 = 0$, and C_i is the volume concentration of pores of size d_i (they are commonly denoted by p_i and can be found from a porosimeter diagram),

$$K_e = \alpha_2 \left(1 - \sum_{i=1}^{m} p_i \right) + 2R \sum_{i=1}^{m} \frac{p_i}{d_i}. \tag{7a}$$

Suppose on an arbitrarily chosen segment of length L there are particles of sizes x from $x = x_{\min}$ to $x = x_{\max}$ with a probability density distribution $\rho(x)$.

The total number of particles encountered by a beam in the segment of length L is clearly

$$N = \int_{x_{\min}}^{x_{\max}} \rho(x)\, dx.$$

Their total length is

$$h = \int_{x_{\min}}^{x_{\max}} x\rho(x)\, dx,$$

and the quantity

$$\int_{x_{\min}}^{x_{\max}} \frac{x}{L} \rho(x)\, dx = \int_{x_{\min}}^{x_{\max}} C(x)\, dx \tag{8}$$

is the volume concentration of the particles. Substituting this expression into Eq. (7) we find

$$K_e = \alpha_2 + (\alpha_1 - \alpha_2) \int_{x_{\min}}^{x_{\max}} \frac{x}{L} \rho(x)\, dx + \frac{2R}{L} \int_{x_{\min}}^{x_{\max}} \rho(x)\, dx. \tag{9}$$

Multiphase System with a Continuous Distribution of Particle Sizes. Substituting Eq. (8) into (6) we obtain

$$K_e = \alpha_n + \sum_{i=1}^{n-1} \frac{2R_i}{L} \int_{x_{\min}}^{x_{\max}} \rho_i(x)\, dx + \sum_{i=1}^{n-1} (\alpha_i - \alpha_n) \int_{x_{\min}}^{x_{\max}} \frac{x}{L} \rho_i(x)\, dx \tag{10}$$

or

$$K_e = \alpha_n + \sum_{i=1}^{n-1} (\alpha_i - \alpha_n) \int_{x_{\min}}^{x_{\max}} C_i(x)\, dx + \sum_{i=1}^{n-1} 2R_i \int_{x_{\min}}^{x_{\max}} \frac{C_i(x)}{x}\, dx. \tag{10a}$$

All the preceding expressions for K_e can be obtained as special cases of (10).

In conclusion, we comment briefly on the choice of parameters appearing in the formulas.

The value of R depends strongly on the angle of incidence of the radiation on the phase boundary. Since for radiation heat transfer inside a material the rays are incident on the surface at very different angles, the value of R in the equations must be replaced by its average value, the hemispherical reflection coefficient. Since diffraction effects are not taken into account in calculating K_e by the proposed model, Eqs. (3)-(10) should be applied only to particles which are much larger than the wavelength corresponding to the maximum of the thermal radiation at the given temperature.

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INVESTIGATION OF THE HEAT AND MASS TRANSFER BETWEEN PROPELLANT COMBUSTION PRODUCTS IN AN EVAPORATING FLUID IN APPARATUS WITH SUBMERGED BURNERS

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Generalized dependences are found to determine the equilibrium depth of submersion of a burner in evaporators with submerged burners.

Apparatus with submerged burners (ASB) are among heat exchangers of bubble type, in which the heat-exchange intensity is ordinarily characterized by the heat-elimination coefficient referred to the volume of liquid or gas — liquid layer above the grating. In connection with the fact that the ASB operates in a thermal equilibrium mode between the fuming gases leaving the apparatus and the evaporating liquid, these volumes can significantly exceed the volume of the active heat and mass transfer zone. Hence, the volume coefficients of heat elimination do not characterize the kinetics of the process in an ASB. Under these conditions, the main parameter to be determined for the heat and mass transfer process becomes the magnitude of the equilibrium depth of burner submersion at which thermal equilibrium sets in. The more intense the heat transport, the smaller the equilibrium depth of burner submersion, and, therefore, the lower the hydraulic drag of the apparatus.

On the basis of an analysis of the differential equations describing the heat and mass transfer in a gas — liquid layer, and the heat balance — heat elimination equation, the general form of the functional dependence for the equilibrium depth of burner submersion h_e [1] was found:

$$\bar{h}_e = \frac{h_e}{d} = c\,\mathrm{Ar}^m \Theta^n \left(\frac{\rho''}{\rho'}\right)^p \left(\frac{l}{d}\right)^q. \tag{1}$$

The thermal equilibrium can be estimated by means of the temperature of the vapor — gas mixture leaving the apparatus, which diminishes with the increase in depth of burner submersion and takes on a constant value when

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