TRANSIENT HEAT TRANSMISSION THROUGH DISPERSE MEDIA DURING SHORT CONTACT TIMES

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For an analysis of heat transmission through disperse media during short thermal contact times, the bulk of a disperse medium is simulated by equivalent electrical networks.

During a short contact between a disperse medium and a heat emitting surface there is no time for the effective properties of the material to assert their influence on the heat transmission, and the process is then determined by the thermal conductivity of the gas in the pores as well as by the roughness of particle and wall surfaces. In view of this, it is of practical interest to know the applicability limits for the Fourier equation of heat conduction when this equation involves the effective properties of a disperse medium.

Transient heat transmission through a disperse medium during short contact times τ was considered earlier in [1-4]. The differential equations of transient heat conduction through disperse media in [1, 2] were proposed on the basis of an extremely systematic structure of that medium. As a result, the exclusive role of contact resistance at $\tau \to 0$ [5] was ignored and the equivalent network in [1] simulating the disperse medium would fail the applicability test under limiting conditions.

In [3] the magnitude of the thermal resistance was related to the thermal conductivity of the disperse medium, at variance with prevalent concepts about the heat conduction mechanism in disperse media at $\tau \to 0$.

The model of a disperse medium according to [4] was based on some hypothetical structure of solid particles near the wall and on a gap between particles and wall surface.

We note that the comparison made in [1-4] between theoretical or calculated values and test data is not sufficiently convincing, inasmuch as neither the structure of the disperse medium near the heat emitting surface nor the roughness of particle and wall surfaces were determined in the tests, apparently because of the complexity of such measurements.

In view of all this, it is worthwhile to analyze the transient heat transmission through disperse media with the aid of mathematical models.

The conventional procedure for analyzing transmission processes in disperse media is to represent the bulk as a structure with a definite distribution of particles. In processes occurring within short contact times, most significant is the distribution of particles in the first row adjacent to the heat emitting surface. According to [6], stationary spherical or irregular grains are cubically packed in the boundary layer. On this premise, then, one can use electrical analogs for analyzing the properties of a disperse medium in the boundary layer and define the parameters of a linear equivalent electric circuit simulating the disperse medium so that the subsequent analysis of transient heat transmission will become rather simple.

An elementary cell of the bulk adjacent to the wall can be represented as a cube or a cylinder filled with gas and circumscribed around a solid particle. It has been shown in [7] that in the cylindrical case the cell diameter of this artifact must be $d = 1.128\ d_S$. The properties of an axially symmetric elementary particle in the boundary layer were thus analyzed on a resistance network under the following assumptions:

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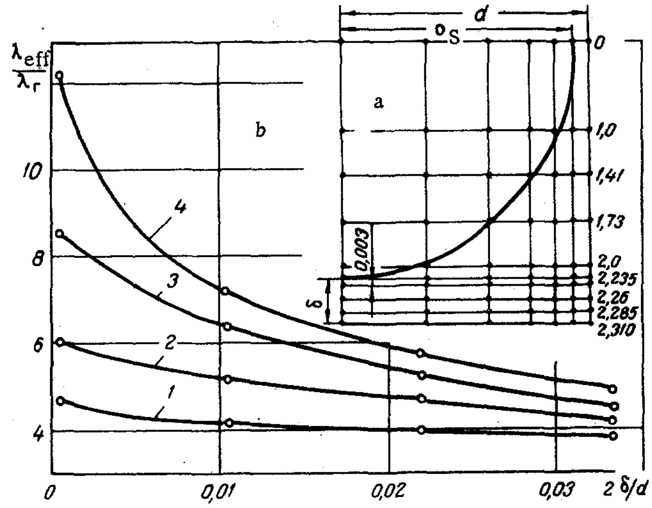

Fig. 1. Elementary cell in the boundary layer of a disperse medium: (a) discretization scheme, (b) effective thermal conductivity for λ_S/λ_G = 12.5 (1), 25 (2), 50 (3), 100 (4).

a) the solid particles are spherical;

b) the microroughness of particle surfaces form a "crown" around the particles which make the contact between them;

c) radiative and convective heat transmission are negligible;

d) the temperature-dependence of thermal conductivity in the two-phase system may be approximated by average coefficients.

In view of the symmetry of a cylindrical elementary cell in the boundary layer, only one quadrant was simulated on the resistance network.

The discretization of a selected region is shown schematically in Fig. 1a. For depicting the spherical surface of a particle more precisely, the discretization interval was made nonuniform so that the nodal points fell on the inner cell boundary

In our tests $\lambda_{eff,I}$ and R_c were determined for various values of λ_S/λ_G and $2\delta/d$. The contact resistance R_c was assumed equal to the thermal resistance of the gas layer between the heat emitting surface and a solid particle:

$$R_c = \frac{1}{\lambda_G} \cdot \frac{l_{equ}}{d_S^2} . \tag{1}$$

The results are shown in Fig. 1b and in Fig. 2. The thickness of the equivalent gaseous gap in the expression for the contact resistance is accurately enough approximated by the expression

$$\lg \frac{l_{equ}}{d} = 0.595 \lg \frac{2\delta}{d} - 0.13. \tag{2}$$

If the components of the effective resistance are known for an elementary cell in the boundary layer, then the disperse medium can be represented by the linear equivalent network shown in Fig. 3a. In setting up this network we assumed the specific heat of the gas to be negligible. The circuit elements of the first zone, simulating the boundary layer of particles, were designed on the basis of data in Fig. 1b and Fig. 2. The circuit elements of the second zone, simulating the buried (second, third, etc.) rows of particles, were designed on the basis of the total effective thermal conductivity of the disperse medium after the latter had been discretized with intervals equal to d_S. The validity of this approach to the problem was subsequently verified.

With the aid of the network shown in Fig. 3a, simulating a disperse system, the transient heat transmission through a granular bed during short contact times τ was analyzed on a model 2-IGL-2-10-4 hydrointegrator.

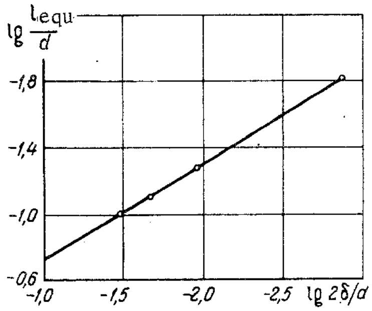

Fig. 2. Equivalent thickness of a gap with contact resistance.

The discrete elements of the simulating network were designed according to the following procedure:

1. For given values of λ_S, λ_G, and ε_{II}, the effective thermal conductivity of the second zone $\lambda_{eff,II}$ was calculated by the Gel'perin formula

$$\frac{\lambda_{eff}}{\lambda_G} = 1 + \frac{(1-\varepsilon)(1-\lambda_S/\lambda_G)}{\lambda_G/\lambda_S + 0.28\varepsilon^{0.63(\lambda_S/\lambda_G)^{0.18}}} \tag{3}$$

2. The thermal resistance of the R-elements in the second zone was determined according to the formula

$$R_{II} = \frac{1}{\lambda_{eff,II}} \cdot \frac{s_{II}}{d_S^2}.$$

3. The thermal capacitance of the C-elements in the second zone was determined from known values of c_S, ρ_S, ε_{II}, and s_{II}:

$$C_{II} = c_S \rho_S (1-\varepsilon_{II}) d_S^2 s_{II}.$$

4. For the porosity of the first zone $\varepsilon_I = 0.476$ with known values of λ_S and λ_G, the effective thermal conductivity of the boundary layer $\lambda_{eff,I}$ was determined according to formula (3).

5. For known values of λ_S/λ_G and $\varepsilon_{eff,I}$, the relative roughness of particle surfaces $2\delta/d$ was determined with the aid of Fig. 1b.

6. The equivalent thickness of the gaseous gap l_{equ}/d in the expression for the contact resistance was calculated according to formula (2).

7. The contact resistance of the boundary layer of particles was calculated as

$$R_c = \frac{1}{\lambda_G} \cdot \frac{l_{equ}}{d_S^2}.$$

8. The thermal resistance and the thermal capacitance of the boundary layer were found as follows:

$$R_I = \frac{1}{\lambda_{eff,I}} \cdot \frac{d+2\delta}{d_S^2}, \quad C_I = c_S \rho_S \frac{\pi d_S^3}{6}.$$

In our tests we varied λ_S/λ_G, ε_{II}, s_{II}, and the discretization interval for zone I. The results have been evaluated in Nu$-\tau^*$ coordinates, as shown in Fig. 3b, c, d.

According to Fig. 3b, varying the discretization interval for zone II has almost no effect on the heat transmission through the disperse bulk during short contact times τ. Therefore, in subsequent tests the interval was fixed at $s_{II} = d_S$.

According to Fig. 3c, the porosity of the buried zone ε_{II} has also no effect on the thermal flux during short contact times τ.

The discretization interval for zone I has a definite effect on the thermal process. This effect is not noted at $\tau^* \to 0$, however, and remains very small at $\tau^* > 0.05$ (Fig. 3d).

The Nusselt number for short contact times τ is affected most by a variation of λ_S/λ_G, as shown in Fig. 4. Here the hydrointegrator calculations are compared with test data obtained by Simchenko [8] and with calculations according to the formula

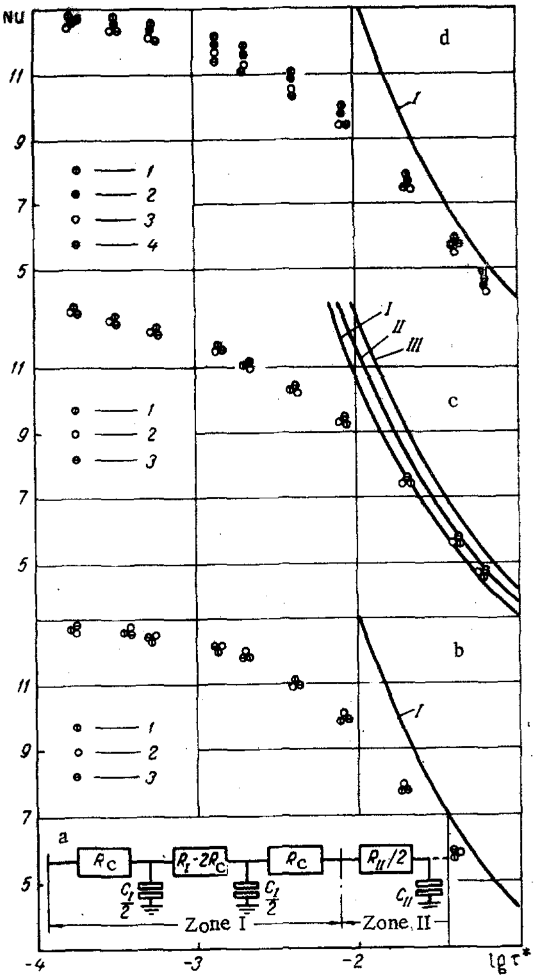

Fig. 3. Linear equivalent network simulating a disperse medium and heat transmission through it during short contact times τ: (a) equivalent circuit diagram; (b) effect of discretization interval for the buried zone on the heat transmission with $\lambda_S/\lambda_G = 100$ and $\varepsilon_{II} = 0.38$, $s_{II}/d_S = 0.5$ (1), 1.0 (2), 1.5 (3), calculated according to formula (4) (I); (c) effect of porosity of the buried zone on the heat transmission with $\lambda_S/\lambda_G = 100$ and $\varepsilon_{II} = 0.44$ (1), 0.41 (2), 0.38 (3), calculated according to formula (4) respectively (I, II, III); (d) effect of discretization interval for the boundary zone on the heat transmission with $\lambda_S/\lambda_G = 100$, $\varepsilon_{II} = 0.38$, and a particle represented by one segment (1), two segments (2), three segments (3), five segments (4).

$$\mathrm{Nu} = \sqrt{\frac{\lambda_{\mathrm{eff,\,II}}\, c_S (1-\varepsilon_{II})}{\pi\tau}} \cdot \frac{d}{\lambda_G}. \tag{4}$$

According to Fig. 4, the hydrointegrator curves for $\tau^* > 0.05$ either coincide with or run parallel to the curves calculated by formula (4). This leads to the conclusion that the effects of a discrete structure and of a higher porosity at the heat emitting surface level off at $\tau^* > 0.05$ and that heat transmission through this layer is determined only by the effective characteristics of the disperse medium.

Our study indicates that during any sufficiently short contact time τ there is no Nu = const range. At $\tau^* < 0.001$, however, the variation in the absolute value of the Nusselt number is slight and can hardly be measured in a thermophysical experiment.

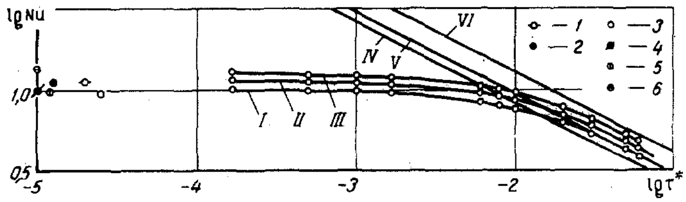

Fig. 4. Effect of ratio λ_S/λ_G on the heat transmission at low values of τ: thermal flux in the simulating network, calculated on the hydrointegrator for $\lambda_S/\lambda_G = 25$ (I), 50 (II), 100 (III); calculated by formula (4) for $\lambda_S/\lambda_G = 25$ (IV), 50 (V), 100 (VI); test values in [8] for particles with a diameter $d_S = 0.39$ mm (1), 0.93 mm (2), 2.07 mm (3), 3.05 mm (4), 5.05 mm (5), limit of Nu according to the equivalent network (6).

The results obtained here indicate that the effective thermal conductivity of buried layers in a disperse medium does not influence the heat transmission during short contact times τ. Therefore, the test results in [1] pertaining to the dependence of thermal fluxes on the effective thermal conductivity of such layers must be explained by the influence of the ratio λ_S/λ_G alone. In view of this, the suggestion that the heat transmission during the "critical" period ($\tau^* < 0.05$) be described by relations which account for the effective characteristics of the disperse medium does not seem justified.

NOTATION

λ is the thermal conductivity;
c is the specific heat;
ρ is the density;
d is the diameter;
2δ is the gap between particles;
l_{equ} is the equivalent thickness of a gaseous gap in the expression for the contact resistance;
R is the thermal resistance;
C is the thermal capacitance;
s is the discretization interval;
R_c is the contact resistance;
τ is the time;
ε is the porosity;
$Nu = \alpha d_S/\lambda_G$;
$\tau^* = \lambda_G \tau / c_S \rho_S d_S^2$.

Subscripts

S denotes solid particle;
G denotes gaseous phase;
eff denotes effective value;
I denotes first (boundary) layer or zone;
II denotes second (buried) layer or zone.

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