LITERATURE CITED

1. S. N. Smirnov, Electrophysical Investigations of Heat Carrier Properties [in Russian], Moscow (1985), pp. 101-160.
2. A. D. Buckingham and J. A. Pople, Trans. Faraday Soc., 51, No. 5, 1173-1183 (1955).
3. V. A. Rabinovich, A. A. Vasserman, V. I. Nedostup, and L. S. Veksler, Thermophysical Properties of Neon, Argon, Krypton, and Xenon [in Russian], Moscow (1976).
4. A. P. Beketov, M. P. Beketov, B. P. Golubev, and S. N. Smirnov, Thermophysics of Nuclear Power Plants [in Russian], Sverdlovsk (1982), pp. 52-61.
5. S. N. Smirnov and A. P. Beketov, Teplofiz. Vys. Temp., 23, No. 5, 1013-1015 (1985).
6. M. Lalleland and D. Vidal, J. Chem. Phys., 66, No. 11, 4776-4780 (1977).
7. A. D. Buckingham, Trans. Faraday Soc., 52, No. 2, 747-749 (1956).
8. S. Kelikh, Molecular Nonlinear Optics [Russian translation], Moscow (1981).
9. A. Dalgarno and A. E. Kingston, Proc. R. Soc., 259A, No. 1, 424-429 (1960).
10. N. I. Timoshenko and A. M. Aleksandrov, Experimental Investigation of the Neon Refractive Index and Density in the 100-273 K Temperature Band for Pressures from 6-250 Bar. Dep. in VINITI No. 1429-83, Moscow (1983).

THERMAL CHARACTERISTICS OF WATER FOAMS

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As the size of foam cells increases natural convection arises and the thermal conductivity of the foam starts to grow with the foam ratio remaining constant. The factor that takes into account the effect of convection is determined.

The use of water foams for extinguishing fires has motivated the study of their thermal characteristics: thermal conductivity and thermal diffusivity. On the one hand, the protective layer of foam should make it possible to remove through it a quite intense flux of heat released on the burning surface. On the other hand, heat fluxes due to conduction or radiation, heating this protective layer with a certain intensity, can increase the temperature in the volume of the foam itself to such an extent that the foam will completely evaporate. To make quantitative estimates and predictions of the intensity of the processes indicated above it is necessary to know the effective thermal conductivity λ_e of foams of different origin and structure. Since the thermal conductivity of the gas phase λ_g in air bubbles is approximately one to two orders of magnitude lower than that of water λ_l, of which the liquid interlayers forming the envelopes of the gas bubbles consist, the main heat transfer can be concentrated along the tortuous liquid framework of the foam on the one hand, while the heat flux repeatedly encounters air gaps of bubbles in its path that do not conduct heat well on the other. It is well known, for example, that in a system of granular layers of hard particles "turned inside out" with respect to the foam it is precisely these air interlayers, which contain components of the mixture with relatively low thermal conductivity, that form the main resistance to heat transfer. In building construction, the thermal insulating properties of barriers can be increased by inserting air interlayers, as done, for example, in doubly glazed windows. The principal defect of such air interlayers in barriers is that as the thickness of the cavity increases, convection flows, facilitating heat transfer through the interlayer and degrading its thermal insulating properties, arise. For this reason, instead of macroscopic air interlayers preference is given to cavities filled with small particles of a solid phase (crushed stone, cinders, cotton, wool), the air gaps between which are so small that the convection arising can be neglected in practice. The correction to the effective thermal conductivity caused by natural convection is given by [1]

$$\varphi = 1 + 0.5\,\mathrm{Ra}, \tag{1}$$

where the so-called Rayleigh criterion

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$$\mathrm{Ra} = \mathrm{Gr}\,\mathrm{Pr}\,\lambda_g/\lambda_1 \tag{2}$$

contains the product of the Grasshoff Gr and Prandtl Pr numbers. The number Pr for most gases is close to unity, while the thermal coefficient of expansion $\beta_t = 1/273$. The ratio λ_g/λ_l or λ_g/λ_s is of the order of 100, even for nonmetallic grains, and the contribution of natural convection becomes appreciable for values of Gr of the order of 50-100.

The effective thermal conductivity of a two-phase system λ_e is defined as the coefficient of proportionality between the heat flux q flowing through the layer of the medium, and the temperature gradient, i.e.,

$$q = -\lambda_e \Delta T/\Delta x. \tag{3}$$

The coefficient λ_e should depend on the structural characteristics of the system as a whole. We shall list the chief parameters. The first one is the foam ratio, i.e., the ratio of the foam volume to the volume of the liquid $\beta = (V_g + V_l)/V_l$. For comparison we give the analogous parameters usually characterizing a granular medium with gas-filled gaps: the relative fractions of the components — the porosity $\varepsilon = V_g/(V_g + V_s)$ and the volume concentration of the solid phase $1-\varepsilon = V_s/(V_s + V_g) = 1/\beta$, whence $\varepsilon = 1-1/\beta = (\beta-1)/\beta$. The next structural characteristic of the foam is the dispersity, defined as the average diameter of the air bubbles D. The fragmentation of the liquid phase is determined by the average thickness of the liquid films δ, bounding the gas bubbles. The parameters β, D, and δ are interrelated by the obvious relation

$$\beta = k\frac{D}{\delta}, \tag{4}$$

where the coefficient of proportionality k can vary from 1/3 for purely spherical bubbles up to 1 for extremely flat walls of "cubic" cells.

According to the Cavalieri—Aker geometric principle [1, 2], the volume fraction of the gas phase ε must equal the fraction occupied by this phase in any flat section and along any straight line. Based on the character of the heat transfer by a medium whose fraction ε is filled with the gas phase, the foam can be regarded, for example, as a collection of parallel sections with thermal conductivities λ_g and λ_l; then the effective thermal conductivity of the entire system should be determined by the equality

$$\lambda_e = \varepsilon\lambda_g + (1-\varepsilon)\lambda_1 = \lambda_g + (\lambda_1 - \lambda_g)/\beta \tag{5}$$

and should decrease in a hyperbolic fashion, approaching λ_g, as the foam ratio β increases. If, however, the same foam is regarded as a collection of sequential sections with thermal conductivities λ_g and λ_l, then the thermal resistances, the inverse of the thermal conductivities, should be added

$$1/\lambda_e = \varepsilon/\lambda_g + (1-\varepsilon)/\lambda_1$$

or

$$\lambda_e = \lambda_g\lambda_1/[\lambda_1 + (\lambda_1 - \lambda_g)/\beta]. \tag{6}$$

According to the last relation the effective thermal conductivity of the system λ_e should also decrease monotonically from λ_l to λ_g as β increases.

Taking into account the possible differences in the geometric shape of the cells, E. Manegol'd [3] proposed the correlation

$$\lambda_e = \lambda_g + 2k(\lambda_1 - \lambda_g)/\beta, \tag{7}$$

in which, like in the limiting relations (5) and (6), the effective thermal conductivity of the foam is assumed to depend only on one structural parameter — the foam ratio β.

Odelevskii proposed the following formula for calculating the effective thermal conductivity of heterogeneous systems with cubic inclusions, whose centers form a cubic lattice while the faces are parallel [4]:

$$\lambda_e/\lambda_1 = 1 - \varepsilon/[1/(1-\nu) - (1-\varepsilon)/3], \quad \nu = \lambda_g/\lambda_1, \tag{8}$$

which holds for all values of ε from $\varepsilon = 0$ to $\varepsilon = 1$. In particular, the formula (8) enables evaluating the effective thermal conductivity of both spherical foams ($0.74 < \varepsilon < 0.9$) and polyhedral foams ($\varepsilon > 0.9$).

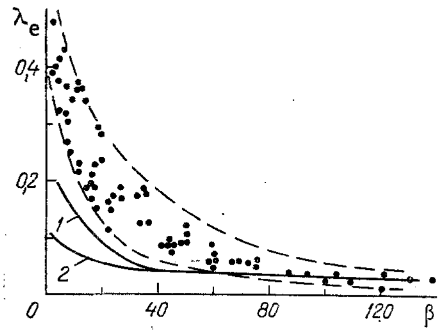

Fig. 1. Effective thermal conductivity versus the foam ratios: 1) Manegol'd's curve (7); 2) Odelevskii's curve (8). λ_e, W/(m·K).

To determine the applicability of the formulas (7) and (8) we performed systematic measurements of the effective thermal conductivity of foams with different foam ratio and dispersity. To increase the reliability the measurements were performed by two methods: stationary and nonstationary.

The imperfection of our apparatus did not permit obtaining foams with fixed and exactly reproducible structural parameters, so that these parameters had to be measured after a given portion of foam was prepared. The foam ratio of the foam prepared was calculated from the ratio of the volume occupied by it to the initial volume of the water with the foaming agent. In different experiments this ratio varied from $\beta = 5$ to $\beta = 140$. The foam prepared was placed into a rectangular cell and photographed, and the average number of bubbles per unit length was calculated from the photograph with a magnification of ×30. The average diameter determined in this manner varied in our experiments from D = 0.3 mm up to D = 5 mm. The foam obtained was quite stable, and its structural parameters did not change over the time required for measuring the thermal characteristics (10-80 sec).

In the stationary state we employed the method of heat flow from a low power pulsed source [5]. The source consisted of a lacquer-coated nichrome wire 0.05-0.10 mm in diameter. A miniature Chromel—Alumel thermocouple, whose indications were continuously recorded, was placed at a fixed distance r_0. When a voltage U was applied to the wire a current I flowed for a short time and the heat power $w_0 = IU/L$ was released per unit length of the wire. The almost instantly obtained heat $Q = w_0\tau_0$ propagated in all directions away from the wire. It is well known [5] that the temperature at a fixed distance r_0 should reach by the time

$$t_{\text{M}} = r_0^2/4a \tag{9}$$

the maximum value

$$T_{\text{M}} = T_0 + w_0/4\pi\lambda, \tag{10}$$

after which the heating drops off, approaching zero, since the temperature maximum shifts to points increasingly farther away from the source.

By measuring experimentally the time t_m at which the maximum is reached and the magnitude of the maximum heating $T_m - T_0$ it was possible to calculate the thermal conductivity λ and the thermal diffusivity a of the foam. Satisfaction of the relation between these quantities $a = \lambda/c_{sp}\rho$ served as an additional check.

Since in our case the heat source was not instantaneous and heat was released over a definite time τ_0, the final working formulas will assume the form

$$a = \varphi_a r_0^2/4t_{\text{M}} \tag{11}$$

and for the thermal conductivity

$$\lambda = \varphi_\lambda w_0/4\pi\,(T_{\text{M}} - T_0). \tag{12}$$

These correction factors φ_a and φ_λ are tabulated as a function of the ratio of times τ_0/t_m in [5]. The filament was heated by switching on a dc current for a time τ_0 from a rectifier, the current strength did not exceed 1 A, while the voltage did not exceed 10 V. The indications of the thermocouple were read according to the deflection of a reflected light spot in a galvanometer, included in the circuit and precalibrated. The maximum heating at the point

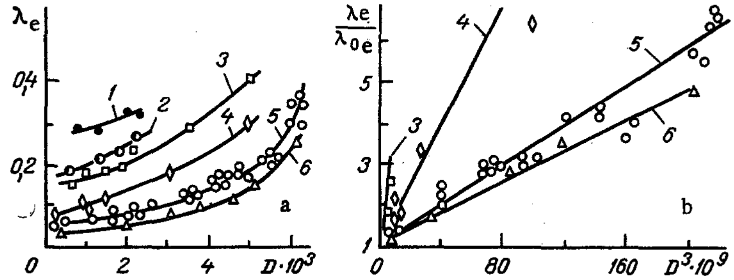

Fig. 2. Effective thermal conductivity of foam versus the average cell diameter (a) and the cell diameter in a cube (b) for a given foam ratio: 1) $\beta = 8 \pm 2$; 2) 17 ± 2; 3) 28 ± 3; 4) 6 ± 5; 5) 100 ± 10; 6) 140 ± 10. $D\cdot10^3$, m; $D^3\times10^9$ m^3.

of observation did not exceed 2-3°C. The cold junction of the thermocouple was submerged in the same foam at a distance greater than r_0, so that when at the point of the hot junction the heating $T - T_0$ reached a maximum the temperature at the location of the cold junction had not yet changed and equaled T_0; this was additionally monitored with a thermometer. The error introduced by the heat capacity of the source as a result of the measurements, not exceeding 3% in our case, was evaluated in [6].

The second, stationary method was based on measurement of the temperature distribution along the heat flow, penetrating successively the foam layer and a reference plate made of a material with a known thermal conductivity λ_{re}. The bottom boundary of the foam, in this case, was a solution of foaming agent, heated up to +50°C. A reference material — a plastic foam plate, a groove in which was filled with water at a temperature of 4-20°C — was placed above the foam. A significant, overall temperature differential and a high heat flux density $q = Q/s$ were created in this manner. This stationary heat flux passed successively through the foam layer with a thickness Δx_1 and through the reference plate with a thickness Δx_2 with the temperature drops ΔT_1 and ΔT_2:

$$q = \lambda_e \Delta T_1/\Delta x_1 = \lambda_{re}\Delta T_2/\Delta x_2. \quad (13)$$

By measuring these thicknesses and temperature drops it is possible to determine the effective thermal conductivity of the foam:

$$\lambda_e = \lambda_{re}\Delta T_2 \Delta x_1/\Delta T_1 \Delta x_2. \quad (14)$$

In order to take into account the lateral leakage of heat in the foam under study, in this method the experimental time dependences of $\sqrt{t}$ versus the temperature drop ΔT were constructed and the values of ΔT and the time intervals over which the lateral heat leakage becomes important were determined from the deviation of the dependence $\sqrt{t} - \Delta T$ from the rectilinear section.

The errors in the measurements of λ_e by both methods equalled 15%. The measurements performed by both methods agree with one another by within the same accuracy.

Results. After the method and setup were perfected, about 100 measurements of the thermal conductivity of foams with different foam ratio and dispersity were performed, primarily by the nonstationary method. The dots in Fig. 1 show the results of these experiments as a function of the foam ratio for the foams studied, and the curves of Manegol'd and Odelevskii, corresponding to the formulas (7) and (8), are presented for comparison. As one can see from the figure, the experimental points lie within a certain spread above these curves, which forced us to assume that λ_e also depends on the dispersity, the possibility of which, due to the appearance of convection within the bubbles, was pointed out at the beginning of the paper. To check this proposition the values of λ_e for foams with different values of D with precisely identical values of β had to be compared. Since, however, our procedure did not permit reproducing the foam ratio exactly in subsequent experiments, we had to select a series of experiments with close ratios. Since $\lambda_l/\lambda_g = 20 >> 1$, for our measurements the formula (7) assumes the approximate form

$$\lambda_e = 2k(\lambda_l - \lambda_g)/\beta. \quad (7^*)$$

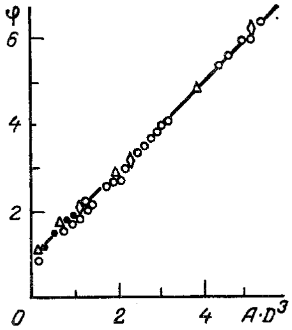

Fig. 3. $\varphi=\lambda_e/\lambda_{0e}$ versus AD^3 (the notation is the same as that used in Fig. 2).

From here we can evaluate the relative error

$$\frac{\Delta\lambda_e}{\lambda_e}=\frac{\Delta\beta}{\beta}, \tag{15}$$

caused by the deviation (spread) in the foam ratio in the selected series. Thus, for example, in the selected series of experiments with the values $\beta = 8 \pm 2$ the possible fluctuation owing to changes in β, in accordance with the estimate (7*), should not exceed 25%. The measured values of λ_e, however, systematically increase from 0.24 to 0.32 W/m•K, i.e., by 33%, as the bubble size increase from 0.5 to 3-5 mm. In the series with the foam ratio $\beta = 28 \pm 3$, however, with the expected spread of up to 10% the effective thermal conductivity increased systematically from 0.15 to 0.40 W/m·K, i.e., by more than a factor two, as the bubble diameter increased from 0.5 to 5 mm.

One can see from Fig. 2a, which shows several series of such curves, that the dependence of λ_e on D is nonlinear. This suggests that there is a correlation analogous to the formula (1) for granular systems. The linear dependence of λ_e, based on the formula (1), on Rayleigh's criterion indicates that there is a linear dependence on the cube of the diameter, appearing in Ra through the criterion Gr, of the particles of the granular medium. Since for a closely packed fill the particle diameters are virtually identical to the sizes of the air cells, in reality it is precisely the latter dimensions that appear in Grasshoff's criterion. Figure 2b shows that by reconstructing the curves $\lambda_e(D)$ in the coordinates λ–D^3 our experimental data do indeed follow a correlation of the type (1), i.e., it can be written in the form

$$\lambda_e=\lambda_{0e}(1+AD^3). \tag{16}$$

Extending these straight lines to the ordinate axis we find the limiting values of λ_{0e}, corresponding to the smallest bubbles, in which, owing to the smallness of Grasshoff's number, convection has not yet fully developed. For different foam ratios they are as follows:

λ_{0e} W/(m·K)	0.25	0.18	0.15	0.12	0.10	0.08	0.07	0.05	0.045
β	10	20	30	40	50	60	80	100	140

If $\varphi=\lambda_e/\lambda_{0e}$ is graphed as a function of AD^3, then all experimental points should fall on a straight line with a slope of 45°. This is checked in Fig. 3.

It follows from Fig. 2a that the effect of natural convection becomes appreciable when the bubble diameter reaches 3 mm. For a temperature difference of $T_m - T_0 = 3°$ this corresponds to the Grasshoff number

$$\mathrm{Gr}=gD^3\beta_t\Delta T/\nu^2=\frac{980\,\mathrm{cm/sec^2}(0.3\ \mathrm{cm})^3}{(0.14\ \mathrm{cm^2/sec})^2}\,1/273\ \mathrm{K^{-1}}\cdot 3\mathrm{K}=15,$$

which is obviously reasonable.

Thus within the limits of the dispersity and foam ratio of water foams that we studied the effect of natural convection on the effective thermal conductivity can be taken into account by introducing a correction factor analogous to (1):

$$\varphi=1+0.5\,\mathrm{Ra}^* \tag{17}$$

by introducing the effective Rayleigh number

$$\mathrm{Ra}^* = \mathrm{Gr}\,\mathrm{Pr}\,\frac{\lambda_g}{\lambda_l}F_a, \tag{18}$$

$$F_a = \begin{cases} 15.38\,(0.64 - \beta\cdot 0.009552)/\Delta T, & 4 < \beta \leqslant 60, \\ 15.38\,(0.08 - \beta\cdot 0.000421)/\Delta T, & 60 < \beta < 200. \end{cases}$$

In conclusion we note that the observed appearance of natural convection in bubbles in foam accompanying weak heating could be of interest for accelerating interphase mass transfer in this system and deserves more detailed study.

NOTATION

λ_e, effective thermal conductivity of foam; λ_g, the thermal conductivity of air; λ_l, thermal conductivity of water; D, diameter of a foam cell; λ_{0e}, thermal conductivity of foam as $D \to 0$; $\varphi=\lambda_e/\lambda_{0e}$, correction factor; $Ra = GrPr\lambda_g/\lambda_l$, Rayleigh's number; $Gr = gD^3\beta_t\Delta T/\nu^2$, Grashoff's number; $Pr = \rho_g c_p \nu/\lambda_g$, Prandtl's number; ν, kinematic viscosity; β_t, thermal coefficient of expansion of air; Δt, temperature drop over one cell; g, acceleration of gravity; q, heat flux; β, foam ratio; ε, porosity; a, thermal diffusivity of the foam; T, temperature; ρ, density of the foam; φ_a and φ_λ, correction factors; A, coefficient; and c_p, heat capacity of air at constant pressure.

LITERATURE CITED

1. M. Z. Aérov, O. M. Todes, and D. A. Narinskii, Apparatus with a Stationary Granular Bed [in Russian], Leningrad (1979).
2. S. A. Saltykov, Introduction to the Stoichiometry of Metallography [in Russian], Erevan (1950).
3. V. K. Tikhomirov, Foams [in Russian], Moscow (1983).
4. V. N. Odelevskii, Zh. Tekh. Fiz., 21, 667-685 (1951).
5. A. V. Lykov (ed.), Methods for Determining the Thermal Conductivity and Thermal Diffusivity [in Russian], Moscow (1973).
6. E. E. Vishnevskii, Tr. Vsesoyuz. Nauch.-Issled. Kinofotoinstituta, No. 2 (25), 73-90 (1958).

METHOD FOR COMPREHENSIVE DETERMINATION OF THERMOPHYSICAL CHARACTERISTICS AND AN ALGORITHM FOR COMPUTER ANALYSIS OF THE EXPERIMENTAL DATA

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The sequence of computer analysis of experimental data in comprehensive determination of the coefficients of thermal conductivity and thermal diffusivity in the Laplace transform domain is presented.

The difficulty of implementing most existing methods for experimental determination of the thermophysical characteristics (TPC) of materials [1] is linked with the complexity of the thermal processes occurring in the system consisting of the measuring cell and the sample of material tested as well as with the need for simple analytic expressions for calculating the coefficients from the experimental data. For this reason, a series of devices for establishing special conditions for heating the sample (maintaining constant or varying according to a definite law the temperatures and heat fluxes on the surfaces of the sample, one-dimensionality of the temperature field in the sample, etc.) are inserted into the experimental apparatus. An example of such methods are the methods of monotonic heating, developed and successfully implemented in [2]. The advantages of this apparatus include a wide temperature range, highly accurate determination of the TPC, and the possibility of evaluating the error in the results. However, the difficulty of setting up and calibrating the apparatus, owing to the fact that a large number of factors must be taken into account, requires that the

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