dimensionless eccentricity; $\bar{\alpha}$, heat-transfer coefficient averaged over the surface of the inner cylinder; $\bar{\alpha} = Q_K/(t_1 - t_2)F_1$; Q_K, heat transferred by convection from the inner to the outer cylinder; F_1, surface area of the inner cylinder.

LITERATURE CITED

1. P. A. Lyukshin and A. S. Lyalikov, Izv. Vyssh. Uchebn. Zaved., Probostr., 14, No. 11 (1971).
2. N. Draper and H. Smith, Applied Regression Analysis, Wiley (1966).

INFLUENCE OF NATURAL GAS EVOLUTION WHILE MELTING ON THE SEPARATION OF THE BOUNDARY LAYER

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It is shown that under conditions of free convection the separation of air bubbles during the melting of ice and snow spheres displaces the point of separation of the boundary layer into the tail region. Relationships are derived for the separation angle as a function of the temperature difference and the porosity of the body.

The understanding and prediction of heat transfer on a melting surface is an extremely important problem of free convection. At the present time the mechanism of heat transfer in the course of melting is not entirely clear. One melting model proposed in [1, 2] started from the concept of the "injection" of melt into the boundary layer and predicted a fall in the heat-transfer coefficient in the course of melting.

We ourselves consider that no less obvious a process is the natural "injection" of gas into the boundary layer of the melt. A frozen solid in fact always contains bubbles. In the course of melting these complicate the hydrodynamic situation and undoubtedly have an effect on heat transfer. So far, however, no special attention has been paid to this. The situation is further complicated by the fact that, for example, in the freezing of water in ice molds the outer layer of ice is transparent and contains few gas inclusions. In order to avoid distortion of the sample shape, research workers have usually only studied the initial stages of melting. It is hardly suprising that according to the conclusions so drawn [3] air bubbles in ice have little effect on heat transfer.

Since heat transfer is governed by the hydrodynamic situation, we shall here consider the special problem as to the influence of bubbles evolved in the course of melting on the separation of the boundary layer.

We made our samples in a spherical demountable mold with an internal diameter of 147 mm. In order to transport the sample and attach a weight to it during immersion we froze a Nichrome wire into the ice. Before the experiment the mold was held in melting ice. After elimination of the supercooling, the sphere was easily extracted from the ice mold and weighed and measured at zero temperature (in a refrigerating chamber). Melting was carried out under conditions of free convection at a constant temperature in a tank with a capacity of 100 liters. In order to visualize the convective flow, aluminum particles were added to the water and illuminated with a flat light beam. At fixed time intervals the profile of the body and the flow of melt were successively photographed.

These observations showed that at $t < 5°C$ there was a rising, unseparated flow; at $t > 5°C$ the flow was downward and the ice sphere behaved as a body of a shape not readily admitting flow around it, the boundary layer undergoing separation. Thereupon the sphere changed

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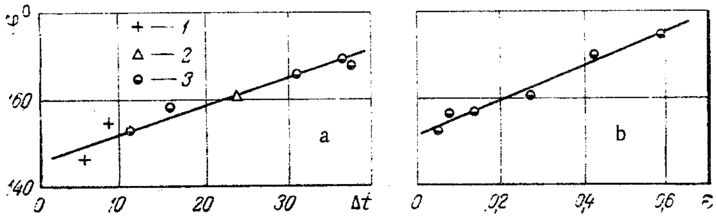

Fig. 1. Angle of separation of the boundary layer as a function of: a) the temperature difference during the melting of ice spheres in water (1, according to [5]; 2, according to [6]; 3, author's own experiments); b) the porosity of the solid phase during the melting of ice and snow spheres in water at +16°C. $\varepsilon = 1 - \rho_T/\rho_M$; Δt, °C.

its classical shape. First, radial hollows developed in the lower hemisphere and the surface acquired an undulating relief. Gas bubbles accumulated at the bottom of the hollows and floated up, while in the center of the lower hemisphere a vault or crater melted out. We took the edges of this vault as the position corresponding to the separation of the boundary layer. Factors determining the separation of the boundary layer included the retardation of the flow in the tail part owing to the dissipation of energy and the development of reverse flow owing to the change in pressure.

We see from Fig. 1a that when ice melts in water the separation point moves in the tail direction as temperature rises. On the one hand, this is a result of the increase in the kinetic energy of the free flow. On the other hand, we notice the absolute values of φ, which exceed the values of the separation angle for transverse flow around nonmelting bodies (φ = 120-140°). We may deduce that there is an additional source neutralizing the process of energy dissipation in the boundary layer. Doubts accordingly arise as to whether the reason for the high φ values is the passage of melt into the boundary layer or whether it arises from the influence of gas bubbles evolved in the melting.

On increasing Δt both the "injection" of melt and the gas evolution increase. Thus the relationship illustrated in Fig. 1a does not provide any unambiguous solution. By making a series of experiments on the melting of ice and snow spheres of various porosities but constant temperature difference (constant "injection" of melt), we were able to separate these effects.

The results presented in Fig. 1b provide a good basis for the assertion that the separation angle of the boundary layer is determined by the intensity of gas evolution. Evidently, the bubbles give rise to vortical structures and neutralize the effect of energy dissipation in the boundary layer, as a result of which the separation point is displaced. This effect appears the more sharply, the greater the temperature difference and the porosity of the body.

Apart from the energy of motion, the bubbles also promote the transfer of a warm mass of liquid to the wall, the cold melt being carried away upward. Thus in the region of bubble separation the temperature of the liquid should rise, which in the case of massive gas evolution will lead to an increase in the temperature gradient, and of course a greater heat-transfer coefficient. On this basis we may readily understand the results of [4, 5], in which the heat-transfer coefficient was found to be higher in the presence of melting than in its absence; this situation was never explained on the basis of the melt "injection" model.

The present results accordingly supplement existing physical concepts as to the mechanism of the melting process and also provide fresh quantitative characteristics.

LITERATURE CITED

1. A. G. Tkachev, "Convective heat transfer in the melting and solidification of a homogeneous medium," Author's Abstract of Doctoral Dissertation, Leningrad Technical Institute of the Chemical Industry (1955).
2. H. J. Merk, "The influence of melting and anomalous expansion on the thermal convection in laminar boundary layers," Appl. Sci. Res., Sec. A, 4, No. 5, 435 (1954).

3. A. G. Tkachev, "Heat transfer during the melting of ice in freely moving water," in: Transactions of the Leningrad Institute of the Refrigeration and Milk Industry [in Russian], Vol. 4 (1953), p. 48.
4. J. M. Dumore, H. J. Merk, and J. A. Prins, "Heat transfer from water to ice by thermal convection," Nature, 172, No. 4375, 460 (1953).
5. J. Schenk and F. A. M. Schenkels, "Thermal free convection from an ice sphere in water," Appl. Sci. Res., 19, 465 (1968).
6. C. R. Vanier and Tien Chi, "Free convection melting of ice spheres," AIChE J., 16, 76, No. 1 (1970).

THE CURTIS–GODSON APPROXIMATION FOR CALCULATING THE RADIATION OF A NONISOTHERMAL GAS

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We obtain a criterion for the applicability of the Curtis–Godson approximation. Using this approximation, we make calculations of the total heat fluxes for nonisothermal steam and carbon dioxide.

Until now no conditions have been obtained for the applicability of the frequently used Curtis–Godson approximation [2, 3]. The more homogeneous and isothermal a medium is, the more accurate the approximation will be. In [2] it was shown, using the example of the transfer problem in a narrow spectrum interval, that the error of the Curtis–Godson approximation may be considerable.

The law of transmission of radiation averaged over a narrow spectrum interval, when we use a statistical model of the absorption bands of a gas, has the form [3]

$$\langle D_\nu \rangle = e^{-\xi_\nu}, \tag{1}$$

where

$$\xi_\nu = \frac{1}{\delta} \int_{-\infty}^{\infty} \frac{a_{\nu\nu'}}{1 + a_{\nu\nu'}}\, d\nu', \tag{2}$$

$$a_{\nu\nu'} = \frac{\delta}{\pi} \int_0^l \bar{K}_\nu(z) \frac{\alpha(z)}{(\nu - \nu')^2 + \alpha^2(z)}\, dz, \tag{3}$$

δ is the average distance between the lines in the band; α is the width of a line (the Lorentz form of the lines); $\bar{K}_\nu$ is the absorption coefficient of the gas averaged over a narrow spectrum interval. We set

$$\alpha(z) = \bar{\alpha} + \alpha'(z). \tag{4}$$

Substituting (4) into (3), we obtain

$$a_{\nu\nu'} = \frac{\delta}{\pi} \frac{\bar{\alpha}}{(\nu - \nu')^2 + \bar{\alpha}^2} \left[\int_0^l \bar{K}_\nu(z)\, dz + \int_0^l \frac{\alpha'(z)}{\bar{\alpha}} \bar{K}_\nu(z)\, dz - \frac{2\bar{\alpha}^2}{(\nu - \nu')^2 + \bar{\alpha}^2} \int_0^l \frac{\alpha'(z)}{\bar{\alpha}} \bar{K}_\nu(z)\, dz + O\left(\int_0^l \left(\frac{\alpha'}{\bar{\alpha}} \right)^2 \bar{K}_\nu(z)\, dz \right) \right]. \tag{5}$$

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