components forming mixture at arbitrary time, kg/m^3; L, total capillary length, m; l, current meniscus coordinate, m; ρ_{10}, initial density of first component, kg/m^3; c_i, relative molecular concentration of vapor components (i = 1, 2) and external gas (i = 3) per unit volume of vapor gas mixture; D_{ij}, binary diffusion coefficient in vapor—gas phase, m^2/sec; x, spatial coordinate, m; c_{10}, c_{20}, relative molecular concentrations of vapor components in surrounding gas at initial time: c_{1S}, c_{2S}, relative concentrations of first and second components above meniscus; c_{30}, c_{3l}, relative molecular concentration of gas forming atmosphere into which evaporation occurs; c^0_{1S}, c^0_{2S}, relative molecular concentrations of vapors of first and second components for pure liquids; N_1, N_2, molar fractions of first and second components; μ_1 and μ_2, molar masses for first and second components, kg/mole.

LITERATURE CITED

1. J. O. Hirschfelder, C. Curtiss, and R. Bird, Molecular Theory of Gases and Liquids, Wiley (1964).
2. R. B. Bird, W. Stuart, and E. Lightfoot, Transport Phenomena, Wiley (1960).
3. F. R. Newbold and N. R. Amundsen, "A model for evaporation of a multicomponent droplet," Am. Inst. Chem. J., 19, 22-30 (1973).
4. M. N. Gaidukov, N. V. Churaev, and Yu. I. Yalamov, "Toward a theory of liquid evaporation from capillaries at temperatures exceeding the boiling temperature," Zh. Tekh. Fiz., 46, No. 10, 2142-2147 (1976).
5. J. F. Richardson, "The evaporation of two-component liquid mixtures," Chem. Eng. Sci., 10, 234-242 (1959).

EFFECT OF ICE SURFACE ORIENTATION ON INTENSITY OF WATER-TO-ICE HEAT TRANSFER UNDER FREE CONVECTION CONDITIONS

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A graphical construction permitting determination of the heat-transfer coefficient for various slopes of an ice surface is proposed.

Heat transfer between water and frozen ground is the main factor causing damage to water reservoirs in regions where the ground does not freeze for years at a time. To predict failure of retaining dams it is necessary to have data characterizing the intensity of thermal processes on the water-frozen soil boundary, in particular, heat-transfer coefficient values.

The profile of the retaining wall may vary greatly, so to simplify calculations it can be approximated by a collection of individual inclined segments. The problem of thermal calculation then reduces to determination of the heat transfer from the water to an inclined plane surface having a negative temperature. In the process of thermal interaction with frozen ground, melting of ice occurs with subsequent removal of the water formed due to a density difference, i.e., the aggregate state of the ice changes and the liquid phase thus produced is removed under the action of free convection.

At the present time the Soviet and foreign literature provides a number of studies of heat transfer to inclined plane surfaces [1-4], but in those studies heat transfer took place with no change in aggregate state of the material. Without considering this factor results in elevated results [5]. Nor is it possible to use results from studies of ice melting with ice specimens in the form of spheres [5-7], cylinders [5], cubes [8], or horizontal surfaces [9, 10], since under free convection conditions the form of the surface has a great effect on heat transfer [1]. Only for the rarely found case of a perpendicular retaining wall can data on heat transfer between water and a vertical ice plate [11-14] be used with assurance.

In studying heat transfer on a water—ice boundary, aside from change in the aggregate state of the ice, another factor producing difficulty is the change in water density with

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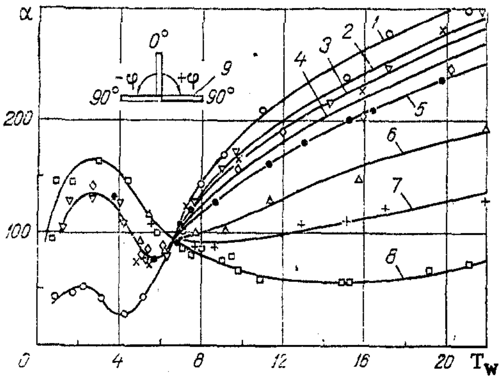

Fig. 1. Heat-transfer coefficient versus water temperature and ice surface orientation: 1) –90°: 2) 0; 3) 15; 4) 30; 5) 45; 6) 60; 7) 75; 8) 90°; 9) ice surface. α, W/m²·deg C; T_w, °C.

temperature [5-7, 11-16]. It is well known that water has maximum density at the critical temperature, which lies in the range 3.94-4.8°C [5-7, 11-16].

The present study will examine the effect of slope of the ice surface on the intensity of heat exchange with the adjacent water. Experimental studies were performed with water temperatures from 1 to 22°C. The experimental specimens were prepared by layered freezing of tap water at a temperature of –1 to –2°C. Specimen size was determined by the dimensions of the wooden frames in which freezing was carried out, the specimens having a surface of 0.325 × 0.365 m. Control specimens were frozen in layers of approximately the same thickness in containers of various sizes and used to determine the ice density. The value used for calculations was $\gamma_i = 8.722$ kN/m³. Before beginning experiments the specimens were maintained in contact with room temperature for some time in order to bring their temperature close to 0°C. They were then placed in a water tank with capacity of 0.5 m³. The specimen was placed on the bottom of the container or on a special mounting bracket (for an angle of –90°). The specimen was maintained in the water for a period of 40-200 min, depending on the water temperature. All experiments were performed in a freezing chamber with air temperature of –0.1 to –0.2°C. Heat-transfer coefficients were determined from the amount of ice melted from the specimen surface.

To measure this quantity, a coordinate grid with nine fixed points was mounted above the surface of the specimen. Measurements were made at these points with sliding calipers to an accuracy of 0.1 mm. Such measurements were performed twice in each experiment: before immersing the specimen and after its removal from the water. The difference between the two measurements determined the amount of ice melted away at each point. The arithmetic mean of the values obtained at the nine points was used in the calculations. Water temperature in the tank was also measured twice during each experiment: several seconds after immersing the specimen and before specimen removal. Water temperature was measured with a laboratory mercury thermometer having gradations of 0.1°C. The mean of the two values was used for calculation. It should be noted that the thermometer was located outside the stratified temperature profile zone established during melting, i.e., sufficiently far from the specimen surface.

Experiments were performed at ice surface inclinations of –90, 0, 15, 30, 45, 60, 75, and 90°. Ice orientation is shown in Fig. 1.

The heat-transfer coefficient was calculated from the experimental data [17]:

$$\alpha = \frac{\Delta\xi\gamma_i L}{(T_w - T_0)\, t}\ \mathrm{W/m^2 \cdot {}^\circ C}. \tag{1}$$

The dependence of heat-transfer coefficient on water temperature and ice surface orientation are shown in Fig. 1. As is evident from the figure, the character of the dependence is quite complex. In analyzing the experimental data it should be noted that at a temperature of about 6.5°C the heat-transfer coefficient proves to be approximately the same for all ice surface angles. Below 6.5°C the coefficient changes significantly for angles between 0 and –90°, with the difference in the values from 0 to-90° being 10-15% in all. Above 6.5°C a

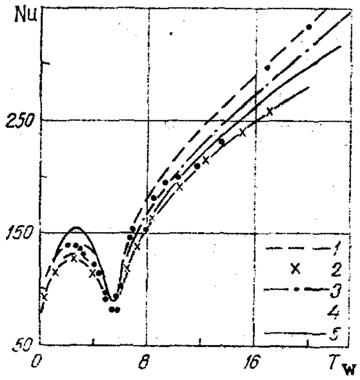

Fig. 2. Comparison of present results with experimental and theoretical data for vertical plate position: 1) [11]; 2) [12]; 3) [15]; 4) [13]; 5) curve 2 of Fig. 1 T_W; °C.

reversed pattern appears: for a change from 0 to −90° the coefficient changes insignificantly, while for angles from 90 to 0° the change is quite large. The maximum deviation of the curves from experimental heat-transfer coefficient values is 10%. A mathematical relationship was established among the curves obtained. In particular, for angles from 0 to +90°

$$\text{at } T_W > 6.5\,^\circ\text{C} \quad \alpha_\varphi = (\alpha_{0^\circ} - \alpha_{+90^\circ}) \cos\varphi + \alpha_{+90^\circ}, \tag{2}$$

$$\text{at } T_W < 6.5\,^\circ\text{C} \quad \alpha_\varphi = (\alpha_{+90^\circ} - \alpha_{0^\circ}) \sin\varphi + \alpha_{0^\circ}. \tag{3}$$

These expressions agree well with the experimental data, and their use is recommended for calculating heat-transfer coefficients at angles between 0 and 90°.

While performing the experiments the following phenomenon was noted: on plates inclined at angles of 0-75° ice melting occurs nonuniformly. At temperatures above critical the ice melts intensely in the upper part of the specimen, while at temperatures below critical the melting is more intense in the lower part. This difference can be explained by a difference in the character of the convective flows produced by heat transfer [5, 11]. At a water temperature below 4°C there is an ascending flow near the ice plate [11]. As this upward moving flow rises to the level of the top of the plate it deviates further away from the plate. As a result the temperature gradient in the boundary layer at the upper edge of the plate decreases [11, 14]. This fact determines the unique pattern of the melting. At a water temperature above 4° there is a descending flow near the plate [11, 14] and the reverse effect occurs.

Ice melted uniformly from the plates inclined at −90 and 90° at all water temperatures.

To estimate the reliability of the results, the data from the experiments performed with a vertical plate (0°) were compared to known experimental [13] and theoretical [11, 12, 14] studies. The data obtained in the present study were recalculated to a plate 0.7632 m long [13]. Results of this comparison (Fig. 2) show quite good agreement. This indicates the possibility of using graphical curves in practical engineering calculations for other angles as well.

One more important fact should be noted. Under turbulent conditions, where $GrPr > 2 \cdot 10^7$, the heat-transfer coefficient for vertical and horizontal surfaces is independent of linear dimensions [17-20], since the heat-transfer process under such conditions is self-similar. The same may apparently be assumed of inclined plates.

All the experiments performed occurred under turbulent regime conditions, as in [13]. The good agreement of experimental data for 0.365- and 0.7632-m-long plates indicates that they may be used to calculate heat transfer to ice plates of very large dimensions, such as inclined portions of retaining walls and the ice surface cover of water reservoirs, in connection with which, the graphical dependence of heat-transfer coefficient for a plate position of −90° will be of interest to hydrological engineers.

NOTATION

α, heat-transfer coefficient from water to ice, $W/m^2 \cdot {}^\circ C$; $\Delta\xi$, amount of ice melted, m; γ_i, mean volumetric weight of ice, kN/m^3; L = 334.32 kJ/kg, specific heat of ice fusion; T_w, mean water temperature, °C; T_o, ice surface temperature, °C; t, specimen maintenance time in water, h; φ, angle of inclination of ice surface, deg; $Gr = \beta g l^3 T_f/\nu^2$, Grashof number; $Pr = \nu/a$, Prandtl number; $Nu = \alpha/\lambda$, Nusselt number; β, temperature coefficient of volume expansion, 1/°C; g, acceleration of gravity, m/sec^2; l, plate length, m; $T_f = (T_w - T_o)/2$, controlling temperature, °C; ν, kinematic viscosity, m^2/sec; a, thermal diffusivity, m^2/sec; λ, thermal conductivity, $W/m \cdot {}^\circ C$.

LITERATURE CITED

1. Vlit and Ross, "Turbulent natural convection on upward and downward directed surfaces with constant thermal flux," Teploperedacha, No. 4, 57-64 (1975).
2. Vlit, "Local heat transfer under natural convection conditions on inclined surfaces with constant thermal flux applied," Teploperedacha, No. 4, 63-72 (1969).
3. T. Fujii and H. Imura, "Natural-convection heat transfer from a plate with arbitrary inclination," Int. J. Heat Mass Transfer, 15, No. 4, 755-767 (1972).
4. K.-E. Hassan and S. A. Mohamed, "Natural convection from isothermal flat surfaces," Int. J. Heat Mass Transfer, 13, No. 12, 1873-1886 (1970).
5. A. G. Tkachev, "Heat exchange in ice melting," in: Icometric Questions in Hydroenergetics [in Russian], Gosénergoizdat, Moscow—Leningrad (1954), pp. 159-164.
6. A. G. Tkachev, "Experimental study of convective heat exchange melting and solidification," Kholodil. Tekh., No. 2, 9-13 (1958).
7. I. M. Dumore and H. I. Merk, "Heat transfer from water to ice by thermal convection," Nature, 172, No. 4375, 460-461 (1953).
8. V. N. Filatkin, "Study of heat exchange in ice melting in a free flow," Kholodil. Tekh., No. 4, 23-25 (1960).
9. Y. C. Yen, "Onset of convection in a layer of water formed by melting ice from below," Phys. Fluids, 11, 1263-1270 (1968).
10. Y. C. Yen and F. Galea, "Onset of convection in a water layer formed continuously by melting ice," Phys. Fluids, 12, 509-516 (1969).
11. Wilson and Li, "Melting of an ice wall in fresh water with free convective motion," Teploperedacha, No. 1, 14-20 (1981).
12. C. R. Vanier and C. Tien, "Effect of maximum density and melting on natural convection heat transfer from a vertical plate," Chem. Eng. Progr. Symp. Ser., 64, 240-254 (1968).
13. M. S. Bendell and B. Gebhart, "Heat transfer and ice-melting in ambient water near its density maximum," Int. J. Heat Mass Transfer, 19, 1081-1087 (1976).
14. Wilson and Vaiyas, "Velocity profiles near a vertical ice surface melting in fresh water," Teploperedacha, No. 2, 145-152 (1979).
15. B. Gebhart and J. C. Mollendorf, "Buoyancy-induced flows in water under conditions in which density extremum may arise," J. Fluid Mech., 87, 673-708 (1978).
16. Chzhen and Takuchi, "Non-steady-state free convection in a water-filled horizontal tube cooled at a constant rate to temperatures near 4°C," Teploperedacha, No. 4, 52-59 (1976).
17. M. A. Mikheev and I. M. Mikheeva, Fundamentals of Heat Transfer [in Russian], Énergiya, Moscow (1977), p. 343.
18. A. V. Lykov, Heat-Mass Transfer (Handbook) [in Russian], Énergiya, Moscow (1971), p. 560.
19. R. J. Goldstain, E. H. Sparrow, and D. C. Jones, "Natural convection mass transfer adjacent to horizontal plates," Int. J. Heat Mass Transfer, 16, No. 5, 1025-1034 (1973).
20. W. H. McAdams, Heat Transmission, McGraw-Hill (1954).