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THAWING OF POLYMER-BEARING ICE IN MOVING WATER

G. I. Smorygin and E. N. Salomatin

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We present data on an experimental investigation of the effect of decreasing the intensity of thawing of polymer-bearing ice in a flow of water. The results obtained are generalized in dimensionless form. Heat transfer coefficients obtained for ordinary thawing ice and for polymer-bearing thawing ice are compared. The mechanisms underlying the decrease in the intensity of thawing of polymer-bearing ice in streams of water moving along the surface with different velocities and temperatures are considered.

It is known that high-molecular compounds consist of long branched or unbranched molecules with a multitude of functional groups and with a linear dimension of about 1 μm [1]. If several molecules meet in a solution, they are joined together forming an extended chain or a framework. Water molecules turn out to be entrained in the cells of this framework, their motion becomes restricted, and the liquid transforms into a gel or jelly. However, so that jellies can be formed, the concentration of the polymer in water should be rather high: 0.5% for gelatin and 5% for polyacrylamide.

Let us consider the process of crystallization of a weak polymer solution.

As ice grows, the moving crystallization front ejects dissolved molecules of high-molecular compounds, and they are collected near the front, increasing in concentration by one or even two orders of magnitude. Having reached the critical concentration of the formation of a gel, the molecules are bound together forming a kind of a dynamic membrane. Water reaches the front by flowing through this membrane. This gives rise to a force of hydrodynamic origin that presses the layer of the gel against the phase change interface. As soon as the spacing between the gel and ice becomes equal to $10^{-4}-10^{-5}$ cm, in the water film between the membrane and ice the forces of a disjoining pressure start to act that obstruct the further approach of the gel toward the ice. Depending on which of the forces dominates, the dynamic membrane can enter the ice or be repelled to the solution [2]. This is the manner in which a microblock structure is formed consisting of cells of pure ice separated by gel membranes formed at rather small initial concentrations of the solution (0.01%).

At crystallization rates exceeding $5 \cdot 10^{-5}$ m/sec, the polymer molecules enter the ice virtually without their redistribution in the solution. In this case, a uniform content of the polymer in the ice is observed [2].

When such an ice is thawing, the captured molecular chains become exposed, remaining to be fastened at one end to the ice, while a gel or a highly viscous layer is formed at the other end, which restricts the motion of water near the ice surface (Fig. 1).

Experimental Procedure. Experimental investigations for determining the intensity of thawing of pure ice and of polymer-bearing ice in a stream of water are conducted in a closed hydrodynamic loop with a closed channel* (Fig. 2). The setup consists of a tank 10 of $1.0 \times 1.0 \times 0.75$ m with external heat insulation to prepare the water. The tank contains a vaporizer 11 from a refrigerator compressor 9 for cooling and tempearture control of the water circulating through the loop with the aid of a pump 8. The working channel of the loop includes a flow equalizer 3, a settling section 2 (of rectangular cross section of size 10×200 mm^2 and length 40 cm), a test section 12, and a flow measuring section 14. The test section consists of a channel 13 of width 200 mm, height 10 mm, and length

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* The loop was designed and fabricated with the help of A. I. Yudin.

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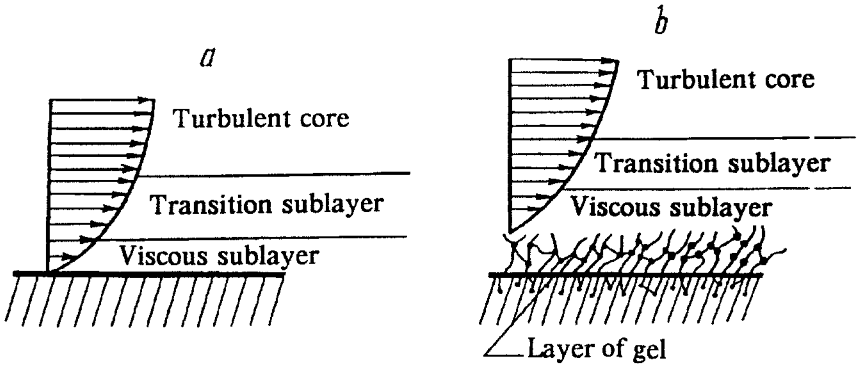

Fig. 1. Structure of turbulent flow above the surface of pure ice (a) and polymer-bearing ice (b).

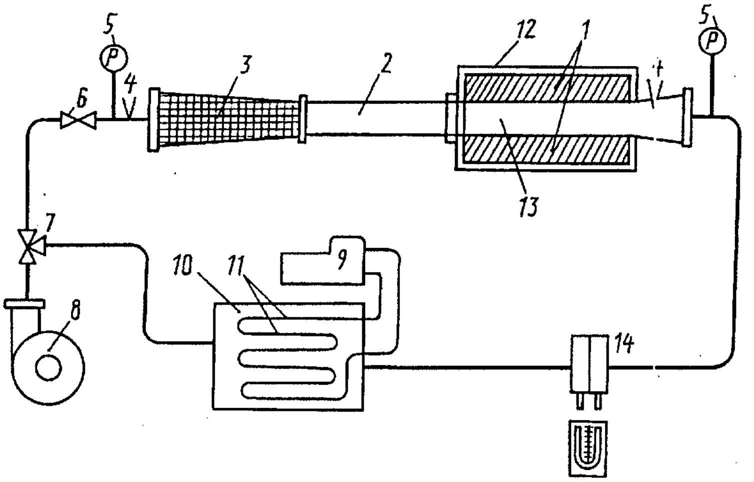

Fig. 2. Diagram of experimental setup.

40 cm and two hermetically sealed vessels 1 (for two samples) of height 8 cm, width 20 cm, and length 40 cm. The entire surface of the test section, except for these vessels, is thermally insulated by a 20-mm-thick foam plastic layer. The temperature at the channel inlet and exit is controlled by temperature probes 4. The pressure in the line is controlled by manometers 5. The elements of the working channel are made from 10-mm-thick Plexiglas, and the remaining portions of the loop are made of polyethylene tubes 42 mm in diameter. The water velocity in the loop is controlled by a valve 6. Using a valve 7, a portion of the total water discharge is released through a by-pass back into the tank. A jet of water from the by-pass line thoroughly mixes the liquid in the tank 10.

The samples were prepared in a refrigerating chamber with a controlled temperature mainly by freezing water in layers (the layers were 3–5 mm thick). The prepared samples were kept for 24 hours at $-1.5-0$ °C with the aid of a thermostatic regulator.

To hold the walls of the holder of samples in the inlet and exit sections at 0°C, flexible polyurethane foam, soaked with water or a solution, was frozen to their end faces. This prevented the intense formation of edge depressions, which promote separation flows.

The profile of a thawing sample was measured in succession by 10 thickness gauges during the entire experiment. To exercise control, after the test the sample was placed for 15–30 min in the refrigerating chamber and then measured. The thawing profile was plotted by 90 points, and the mean value of the destroyed portion of the sample was calculated.

Since the dimensions of the experimental setup are limited, it is necessary to determine experimentally the minimum sample length that would be sufficient for the development of a thawing profile undistorted by boundaries. For this purpose, using inserts we reduced the length of the test section to dimensions of 200, 120, and 40 mm. The results of experiments with samples of various dimensions showed that by decreasing the length of the ice

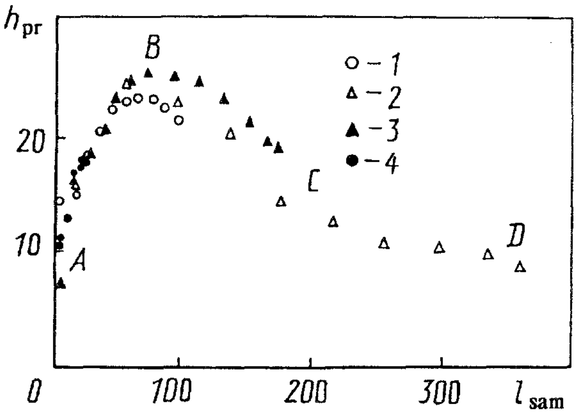

Fig. 3. Profiles of boundary of ice thawing in a stream of moving water at different sample lengths l_{sam}: 1) l = 120 mm; 2) 372; 3) 200; 4) 40. h_{pr}, l_{sam}, mm.

sample we could reproduce a portion of the thawing profile (Fig. 3). However, starting from 200 mm and above, the shapes of the ice-water interfaces remain similar and, consequently, a sample length of 400 mm is sufficient, since it covers section *CD*, which is not distorted by the *ABC* cavity.

To the knowledge of the present authors, the phenomenon noted is observed for the first time and is of interest in itself.

Analysis of Results. The thawing of ice during the motion of water over its surface occurs under conditions of constant removal of the melt by an incoming stream of warm water. The rate of thawing is determined by the intensity of heat and mass exchange between the surface of the ice and water and depends on the temperature distribution in the ice and water, as well as on the conditions of flow.

The processing of the results is complicated because the height of the channel h_0 above the sample increases with time by the magnitude of the thawing layer $h(\tau)$. An increase in the height of the channel leads to a local decrease in the flow velocity above the sample. Another complexity is the formation of a cavity in the ice approximately 9 min after the start of the experiment. After being formed, the cavity develops rather quickly due to the eddy flow of water in it and exerts a strong effect on heat and mass transfer in the remaining portion of the sample as a whole. Therefore, for processing the results of investigations, we shall avail ourselves of the data obtained for a time smaller than the period of the development of the cavity.

We calculate the heat transfer coefficients α by a well-known formula obtained assuming a constant and close to 0°C temperature of the entire sample:

$$\alpha = \frac{L\rho_i\, h(\tau)}{t_w \tau}\,. \tag{1}$$

We determine the relation $h(\tau) = f(\tau)$ at a controlled velocity (u) and temperature of the supplied water (t_w) from the experiments. Using these data, we calculate from formula (1) the heat transfer coefficients of the pure ice and ice composite and obtain a graphical dependence of their change on the mean velocity of water (u_m) in the channel (Fig. 4). Such a dependence can be described by the empirical formula [3]

$$\alpha = C_0 u_m^n\,,$$

where C_0 and n are constants.

Determining C_0 and n for straight lines I and II (Fig. 4), we obtain the following formulas

$$\begin{aligned} \alpha &= 5.13\cdot 10^3 u^{0.93} \quad \text{(pure ice)}, \\ \alpha &= 1.31\cdot 10^3 u^{1.05} \quad \text{(polymer–bearing ice)}. \end{aligned} \tag{2}$$

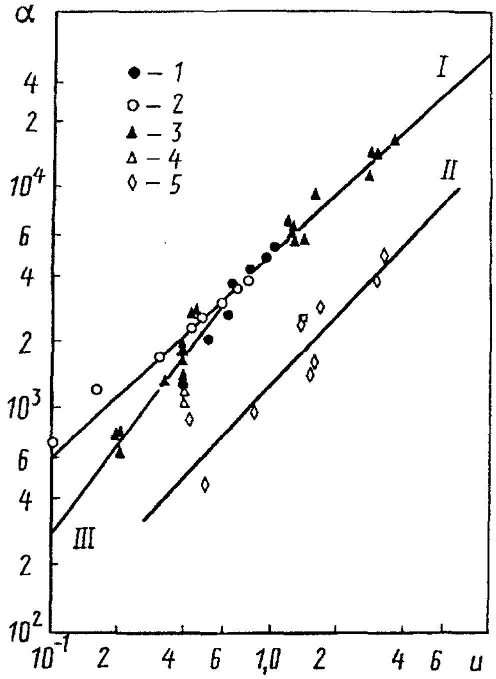

Fig. 4. Coefficients of heat transfer (α) from water moving with different velocities (u) to the surfaces of pure ice and ice composites, according to the data of various authors. Pure ice: 1) data of Ilarov; 2) data of Sokolov; 3) data of the present authors; 4) ice with 0.25% gelatin; 5) ice with 0.5% gelatin (4, 5, data of the present authors). α, W/(m$^2\cdot$°C); u, m/sec.

We should note that, according to our data and those of N. A. Ilarov (straight line III), at water velocities smaller than 0.6 m/sec, a faster dependence of α on u_m is observed for pure ice, resulting in

$$\alpha = 6.03\cdot 10^3 u^{1.33} .$$

The reason for this phenomenon is elucidated.

To generalize the obtained experimental data on the thawing of ice and ice composite materials in a stream of water, we shall use, instead of particular formulas (2), the relationship between the Nusselt (Nu) and Reynolds (Re) numbers in the form

$$\mathrm{Nu} = C\mathrm{Re}^n ,$$

where C is a constant numerical coefficient.

To calculate Nu and Re, we have two ways to specify the characteristic dimension: use either the primary height of the channel h_0 or the mean height of the channel $h_m = 0.5(2h_0 + h(\tau))$. Then, at $l = h_0$ we obtain $C = 0.027$, $n = 0.93$; at $l = h_m$, $C = 0.021$, $n = 0.95$.

The following are dimensionless relations obtained by various authors on processing the results of the thawing of ice surfaces in a stream of water:

$$\mathrm{Nu} = 0.028\mathrm{Re}^{0.93} \text{ (the data of the present authors)}, \tag{3}$$

$$\mathrm{Nu} = 0.094\mathrm{Re}^{0,8} \text{ (the data of Shatalina [4])}, \tag{4}$$

$$\mathrm{Nu} = 0.022\mathrm{Re}^{0.97} \text{ (the data of Ilarov [5])}, \tag{5}$$

$$\mathrm{Nu} = 0.047\mathrm{Re}^{0.85} \text{ (the data of Sou, et al. [6])}, \tag{6}$$

$$\mathrm{Nu} = 0.078\mathrm{Re}^{0.8} \text{ (the data of Ashton, Kennedy [7])}, \tag{7}$$

$$\mathrm{Nu} = 0.011\mathrm{Re}^{1.01} \text{ (according of Shatalina [4])}. \tag{8}$$

When comparing different experimental data processed in dimensionless form, particular attention should be paid to the selection of a characteristic dimension and determination of the flow velocity in calculations of the Nu and Re numbers. In all of the formulas presented (except for (4)) the depth of the flow is taken to be the characteristic dimension; velocity is calculated from the water flow rate per unit time passing through the flow cross section. In formula (4) the ratio of the volume of the ice sample (V) to its surface (S) is taken as the characteristic dimension l. If we exclude the results that pertain to the thawing of ice frozen-on in the interior of the tube and that were taken into account for the derivation of formula (4)), where the ratio V/S as the characteristic dimension was not physically substantiated, then we obtain formula (8).

If we compare relations (3)-(8) with M. A. Mikheev's generalized formula* [3] without phase transitions on the heat-transfer surface

$$\mathrm{Nu} = 0.021\mathrm{Re}^{0.80}, \tag{9}$$

where the ratio of the 4 × cross-sectional area of the channel to its wetted perimeter is taken to be the characteristic dimension, we note that the values of the exponent n and constant C (with the phase transition taken into account) are usually higher. This is equivalent to the situation in which the heat transfer coefficients of a thawing surface are always higher at the same flow velocities. However, this problem lies outside the scope of the present article.

The introduction of polyoxy and gelatin molecules into ice substantially (by about 4.5 times) reduces the heat transfer coefficient (see relation (2)) and, consequently, the intensity of thawing under the same conditions (Fig. 5). At flow velocities $u_m \leq 0.5$ m/sec, the thawing-out layer of gel, with the initial concentration of the polymer in the ice being ~0.5%, remains indestructible on the ice surface. At velocities above 0.5 m/sec, small pieces of thawing-out gel start to detach from the thawing surface at the end of the experiment (~20 min) and are carried away by a stream of water, leaving a fixed layer of gel thicker than 5 mm on the ice. When the water moves with a velocity of 1.0 m/sec and higher, pieces of gel start to detach from the surface from the very beginning of the experiment, and the surface layer of the gel is reduced to 2–3 mm.

On decreasing the concentration of gelatin in the ice to 0.25%, the flow velocity decreases only by a factor of 1.5–2, whereas the use of polyoxy molecules under the same conditions decreases the heat transfer coefficient by 50% compared with gelatin. The temperature of the incoming water exerts a great influence on the state of the thawing-out gel. An increase in the temperature of water from 3 to 10°C leads to an increase in the heat transfer coefficient of thawing ice containing 0.5% gelatin by a factor of 3, due to the fact that the thickness of the gel, bound mechanically to the ice, was reduced to 1–2 mm.

A Mechanism Underlying the Decrease in the Thawing Intensity of a Polymer-Bearing Ice in a Stream of Water. It is known that a turbulent flow consists of a viscous sublayer, a transition zone, and a turbulent core (see Fig. 1a). The thawing-out polymer molecules, tightly attached to each other and also to the ice, form a zone on the ice-water interface that substantially displaces the turbulent flow profile to the wall layer, that joins the laminar and transition regions, making it thicker (Fig. 1b). The thickness of this zone fluctuates from 1.5 to 15 mm for different polymers.

When Re < 100,000, the thickness of the viscous sublayer ($\delta_{\mathrm{v.s}}$) for the pipes can be estimated by using the empirical formula of [8] $\delta = 62.8 \cdot d\,\mathrm{Re}^{-0.875}$. Calculations show that when $d = 0.01$ and Re = 10,000, $\delta = 0.2$; at Re = 12,000, $\delta = 0.17$ mm; at Re = 20,000, $\delta = 0.11$ mm. Consequently, even at small Reynolds numbers the thickness of the zone of the thawing-out polymer is by orders of magnitude larger than the viscous sublayer and therefore determines the heat exchange between the stream and the ice surface. Let us estimate the effective thermal

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* The formula has this form for small temperature differences (≤ 5°C) and for the channel height-to-length ratio smaller than 0.1.

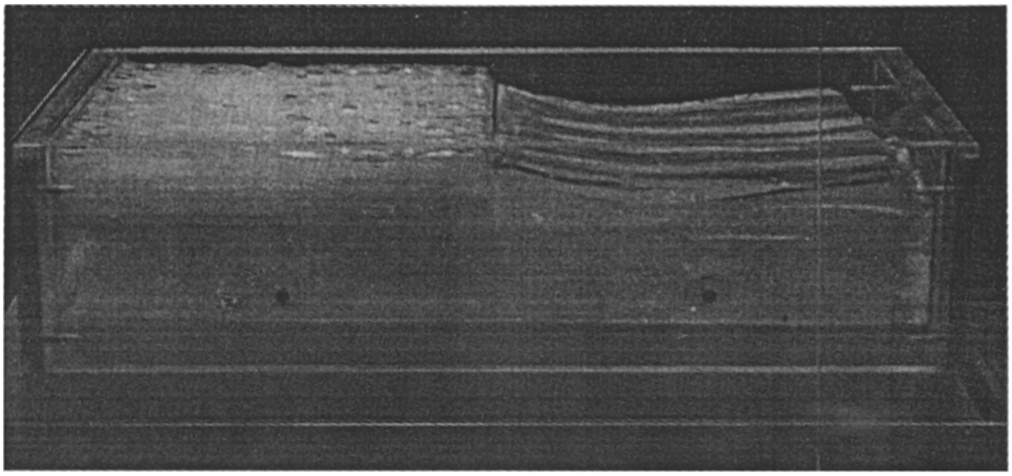

Fig. 5. Sample that thawed for 20 min and that consisted of 0.5% gelatin (left side) and pure ice (right side) in a stream of water (velocity 0.48 m/sec, temperature 2.6°C). The length of the sample is 400 mm.

conductivity of the polymer layer. The density of the heat flux to thawing ice in a steady-state process is defined by the formula

$$q = \rho L \frac{\Delta h}{\Delta \tau}. \tag{10}$$

According to Fig. 1b, with allowance for the layer of thawing-out polymer the heat flux q can be expressed approximately as

$$q = \lambda_{\text{ef}} \frac{t_x - t_s}{h_{\text{p.l}}} = \alpha (t_w - t_x), \tag{11}$$

whence we find

$$\lambda_{\text{ef}} = \frac{q h_{\text{p.l}}}{t_w - q/\alpha}. \tag{12}$$

When ice consisting of a 0.5% gelatin solution thaws in a stream of water moving with a velocity of 1.33 m/sec, $q = 3573$ W/m^2; $h_{\text{p.l}} = 2.5$ mm; $t_w = 2.2$°C. From experimental data for pure ice we adopt $\alpha = 9188$ W/(m^2·°C). Substituting these values into formula (12), we obtain $\lambda_{\text{ef}} = 4.9$ W/(m·°C), which differs by an order of magnitude from the molecular thermal conductivity of water.

In view of the fact that there is only 0.5% of a polymer in the thawing-out layer (this does not influence the molecular thermal conductivity of the water), we conclude that for a flow velocity above 1 m/sec the water in the $h_{\text{p.l}}$ zone is in motion (convective mixing is in effect).

At water flow velocities smaller than 0.7–1.0 m/sec, a gel layer is formed above the ice, which is not destroyed in the process of thawing. To estimate its thermophysical properties, we solve the inverse Stefan problem: we determine the effective thermal conductivity of the thawing-out layer by the known law of phase-change-interface motion.

For this purpose, we solve the following problem:

$$\frac{\partial t_{\text{th.g}}}{\partial \tau} = \frac{\lambda_{\text{ef}}}{c\rho} \frac{\partial^2 t_{\text{th.g}}}{\partial x^2}, \quad x \geq 0; \tag{13}$$

$$-\lambda_{\text{ef}} \frac{\partial t_{\text{th.g}}}{\partial x} = L\rho \frac{dh}{d\tau}, \quad x = h; \tag{14}$$

$$t_{\text{th.g}} = t_x , \quad x = 0 ; \tag{15}$$

$$t_{\text{th.g}} = t_{\text{ph}} = 0 , \quad \tau = 0 ; \tag{16}$$

$$h = \beta \sqrt{\tau} . \tag{17}$$

For the statement of the problem it was assumed that the ice temperature in the process of thawing was equal to 0°C and that the heat transfer coefficients α were so large that the third-kind boundary condition $q = \alpha(t_w - t_x)$ could be replaced by the boundary condition of the first kind $t_w = t_x$ (t_w is the temperature of the water in the stream). The parameter $\beta = 1.48 \cdot 10^{-4}$ m/sec is determined from the graph plotted from the experimental data in the h and $\sqrt{\tau}$ coordinates.

The following transcendental equation is a solution of system (13)-(17):

$$\frac{t_s \exp\left(-\beta^2 c\rho / 4\lambda_{\text{ef}}\right)}{\sqrt{\pi \lambda_{\text{ef}} / c\rho}} = \frac{\rho L \beta}{2\lambda_{\text{ef}}} \operatorname{erf}\left\{ \frac{\beta}{2} \left(\lambda_{\text{ef}} / \rho c\right)^{-1/2} \right\} , \tag{18}$$

whose solution by the method of successive approximations yields $\lambda_{\text{ef}} = 1.17$ W/(m·K), which also differs substantially from the molecular thermal conductivity of water.

Let us estimate the contribution of free convection to the thermal conductivity coefficient of a polymer-bearing thawing-out layer.

Free convection is defined by the Grashof number:

$$\text{Gr} = \gamma g h_{\text{p.l}}^3 \Delta t / \nu^2 ,$$

where $\gamma = 0.6 \cdot 10^{-4}$ 1/°C is the coefficient of thermal expansion of water. Assuming that $h_{\text{p.l}} = 5 \cdot 10^{-3}$ m, $\Delta t = 3$°C, and $\nu = 1.8 \cdot 10^{-6}$ m^2/sec, we find Gr = 67.8. Availing ourselves of the familiar dimensionless relation

$$\lambda_{\text{con}} = 0.473 \, (\text{Gr})^{1/4} ,$$

we obtain $\lambda_{\text{con}} = 1.35$, $\lambda_0 = 0.756$ W/(m·K).

Taking account of the molecular thermal conductivity of water, we obtain $\lambda_{\text{ef}} = \lambda_{\text{con}} + \lambda_0 = 0.756 + 0.56 = 1.3$ W/(m·K), which is close to the value determined above. Consequently, taking into consideration the reduced mobility of water in a gel, we conclude that heat transfer through a thawing-out layer occurs via free convection and molecular heat conduction.

We should also note the decrease in the rate of thawing of a polymer-bearing ice due to a decrease in the roughness of the thawing surface when protrusions and depressions are covered by the thawing-out polymer.

Finally, there are also hydrodynamic factors that reduce the thawing rate: thawing-out polymer molecules entrained by a stream of water influence the hydrodynamics of the flow by inhibiting its turbulence [9]. However, analysis of this phenomenon lies outside the scope of the present article.

Thus, employing modeling in a hydrodynamic loop we found that when an ice surface thaws in a stream of water cavities appear on its natural inhomogeneities or in places of its contact with other materials, which, increasing in size, lead to a general extension of the surface of heat exchange with the moving water and, as a result, to enhancement of the thawing process. We managed to prove that the introduction of a water-soluble polymer into ice at concentrations starting from 0.2% inhibits the development of cavities on its surface at water-flow velocities of from 0.2 to 1.5 m/sec (the region we investigated). Moreover, the intensity of the thawing of ice containing a polymer (gelatin) in concentrations from 0.25 to 0.5%, is 3–5 times smaller than that of pure ice.

The ice composite material obtained can be used as a protecting layer when building ice spillways at the North State Power Plants [10], temporary ice dams, and islands for prospecting drilling [11].

The authors are grateful to A. I. Yudin for data on certain regimes of thawing of pure ice.

NOTATION

L, latent heat of ice thawing; ρ_i, density of ice; λ_w, thermal conductivity of water; $h(\tau)$, thickness of thawed layer at time τ; t_w, temperature of incoming water; α, heat transfer coefficient; $\mathrm{Nu} = \alpha l/\lambda_w$, Nusselt number; $\mathrm{Re} = u_m l/\nu$, Reynolds number; $u_m = [u_0 + u(\tau)]/2$, mean velocity of motion in channel; $u_0 = Q/(bh_0)$, initial flow velocity; Q, flow rate of water passing through channel; h_0, b, height and width of channel; $u(\tau) = Q/(b[h_0 + h(t)])$, flow velocity at time τ; ν, kinematic viscosity of water; l, characteristic dimension; d, tube diameter; λ_{ef}, c, effective thermal conductivity and heat capacity of thawing-out gel layer of height $h_{p.l}$; $t_{th.g}$, t_x, temperatures in thawed gel layer and on its surface; ρ, density of water; ρ, parameter; γ, coefficient of thermal expansion of water; g, free fall acceleration; λ_{con}, thermal conductivity of water due to convection. Indices: p.l., polymer layer; th.g., thawing-out gel layer; v.s., viscous sublayer.

REFERENCES

1. S. R. Rafikov, V. P. Budtov, and Yu. B. Monomov, Introduction to the Physical Chemistry of Polymer Solutions [in Russian], Moscow (1978).
2. V. Melnikov and G. Smorigin, in: Permafrost: Proc. of the 6th Int. Conf. on Permafrost, Pt. 1, Lanzhou, China (1993), pp. 445-460.
3. M. A. Mikheev and I. M. Mikheeva, Fundamentals of Heat Transfer [in Russian], Moscow (1977).
4. I. N. Shatalina, Heat Exchange in the Processes of Freezing and Thawing of Ice [in Russian], Leningrad (1990).
5. N. A. Ilarov, Spillway Water Structures of Low-Head Water Power Plants on Permafrost Foundations, Dissertation for Cand. of Technical Sciences, Moscow (1985).
6. K. S. Sou, F. A. Locker, and J. S. Kennedy, Heat Transfer, 101, No. 4, 27-33 (1979).
7. M. Wolsh, Trans. Soc. Reol., 27, 134 (1978).
8. E. Z. Rabinovich, Hydraulics [in Russian], Moscow (1980).
9. J. L. Lamley, Mechanics, No. 2, 70-89 (1969).
10. O. M. Finagenov, V. I. Khor'kov, and S. G. Shul'man, Ice Spillways [in Russian], Leningrad (1992).
11. G. I. Smorygin and A. I. Yudin, Method for Protection of Hydrotechnical Ice Structure from the Effect of the Heat of Moving Water, Authors's Certificate 1640291 USSR MCI E 02B 17/00.