EXPERIMENTAL INVESTIGATION OF THE COOLING OF THE SYSTEM WATER—ICE—SOIL WHILE A PIPE IS PUT INTO OPERATION

S. A. Karaush

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The article presents the results of the experimental investigation of the start of an underground pipe when a freezing liquid is transported in it.

Problems of heat exchange of a liquid freezing in an underground pipe have been receiving ever increasing attention lately [1-3]. The transport of water and other freezing liquids through pipes placed in frozen soil is often complicated by the formation of a solid phase inside the pipe, which may cause breakdown [4]. The existing methods of the thermal calculation of underground pipes for the starting period [2, 3] require experimental confirmation.

For the visual observation of the ice forming in an underground pipe we used an installation diagrammatically illustrated in Fig. 1. Soil 1 was placed in a heat-insulated wooden jacket 768 × 800 × 1200 mm in size. The lower base of the soil was the cooler 2 in which water with a temperature of 0.5-1.0°C circulated. The water was cooled by the refrigerating device 3. A constant temperature of up to -30°C was ensured on the upper surface of the soil by the upper cooler 4 and the refrigerating device 5 in which a solution of ethylene glycol in water circulated and where the specified regime and the amplitude of temperature fluctuations of the brine relative to the specified value were maintained automatically within ±1°C. The water was cooled in the constant-pressure tank 6 by the refrigerating device 7, and it was supplied via the section of hydrodynamic stabilization 8 with a ratio $l/d = 55$ to the experimental pipe section 9 placed in a soil massif 96 mm below the surface. The pipe was made of stainless steel, with inner diameter 70 mm and 1 mm wall thickness. The experimental section of pipe was 768 mm long. The water circuit was circulatory, for which the overflow tank 10, the circulation pump 11, and the overflow pipe 12 were provided. All the elements of the installation were heat-insulated by a layer of mineral wool 150-250 mm thick to reduce heat losses. The water flow rate was measured by the flowmeter 13 type RÉD-3103, the recording was done by the secondary instrument ÉPID-01. The relative error of the water flow rate was 1%. The thickness of the ice was measured visually through the transparent window 14 with the aid of an ice meter using the lighting device 15 in two sections, 268 and 568 mm from the entrance to the experimental section of the pipe. The absolute error in measurements of the thickness of the ice was up to 1 mm. The water and ice temperatures were measured in four cross sections of the experimental section 37 by calibrated copper—constantan thermocouples, the soil temperature was measured in two sections next to the pipe, and also far from the pipe 35 by the same kind of thermocouples. The temperatures were recorded by an automatic 24-point potentiometer ÉPP-09 with limits of the scale -40 to + 10°C. The relative error in temperature measurements was 1%. The temperature of the brine and of the water in tanks 6 and 10 was additionally measured with laboratory thermometers with a scale division of 0.1°C. Before each experiment was begun, the soil was frozen to more than $\frac{2}{3}$ of its height, and the water in the system was cooled to the specified temperature. The temperatures of the soil, the water, and the brine were measured 2-3 min before the experiment began, and then every 10 min after the start of the experiment. As the start of the experiment we took the instant when water was let into the pipe. Subsequently all the magnitudes were measured once an hour.

The thermophyscial characteristics of the soil in the frozen state were determined experimentally with a maximum error not exceeding 8%, and they are: thermal conductivity 0.85 W/(m·°K); density 1468 kg/m^3; humidity by weight 14.63%. The soil was loam.

On the above-described installation we carried out 17 experiments with laminar and transient water flow, and the principal experimental data are presented in Table 1.

S. M. Kirov Tomsk Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 6, pp. 969-974, June, 1986. Original article submitted February 25, 1985.

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TABLE 1. Principal Characteristics of the Experiments

Water flow at the entrance to pipe	Laminar														Transient		
No. of expt.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Water temp. at entrance to pipe, °C	0,24	0,26	0,23	0,24	0,26	0,69	0,64	0,62	0,62	1,24	1,24	1,16	1,15	1,16	0,28	0,28	0,23
Soil temp. on the surface, °C	—23,0	—23,0	—18,2	—12,0	—12,0	—23,0	—18,8	—18,8	—12,0	—23,0	—23,0	—18,8	—12,0	—12,0	—12,0	—15,0	—19,7
Soil temp. on pipe axis in the natural state, °C	—17,2	—17,8	—14,8	—9,6	—9,4	—18,5	—15,3	—15,3	—9,2	—18,5	—18,5	—14,3	—8,6	—9,1	—11,6	—9,4	—15,0
Reynolds number at entrance to pipe	509	1370	946	512	1330	962	514	1380	951	523	1405	966	532	1400	3580	3580	3580
Reynolds number and profile of ice in section 568 mm from entrance to pipe at the end of the experiment (C: concentric, S: sickle-haped)	1130	2280	2210	874	2220	1600	958	2570	1270	1080	2520	1730	703	1490	7200	4650	17900
	C	C	C	C	C	C	C	C	S	S	S	S	S	S	C	S	C
Duration of expt., h	4	4	6	9	10	5	7	8	11	8	13	12	13	9	13	23	12

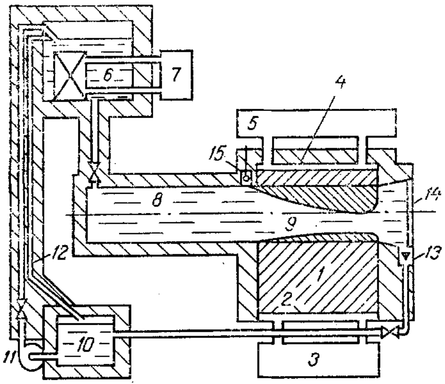
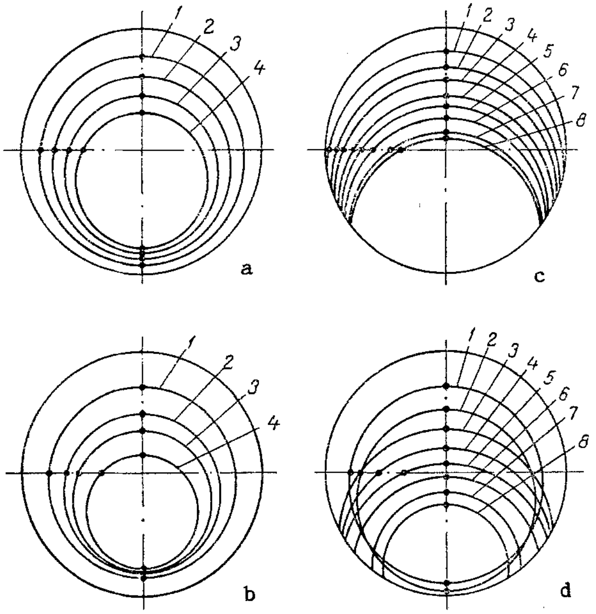


Fig. 1. Basic diagram of the experimental installation.



Experiment No. 2 Experiment No. 10

Fig. 2. Nature of the time-dependent change of the profile of ice along the pipe section: a, c) 268 mm from the entrance into the pipe; b, d) 568 mm from it. The numbers next to the curves indicate the duration of the experiment, h.

A few minutes after cooled water had been let into the pipe, the entire inner surface of the experimental pipe section was covered by a uniform thin layer of ice which subsequently, in dependence on the experimental conditions, either continued to grow or began to melt. Growth or melting of the ice was determined by the heat-accumulating ability of the soil massif, its temperature, and the temperature of the water flowing into the pipe. Inside the underground pipe over its section we later observed two profiles of the ice layer: a concentric one and a sickle-shaped one. The concentric profile was found with "rigid" conditions on the outside of the pipe and with temperatures close to 0°C of the water flowing into the pipe. For the second experiment this is shown in Fig. 2a, b. When the temperature of the water flowing into the pipe is "higher" (above 0.5°C), the profile of the ice is sickle-shaped, as shown for experiment No. 10 in Fig. 2c. The concentric profile of ice forming at such temperatures may later change into a sickle-shaped one, as shown in Fig. 2d. With water temperatures above 0.5°C the sickle-shaped ice profile at the initial pipe section may change further on into a concentric profile toward the end of the pipe, and in the pipe there occurred simultaneously melting of the ice in sections close to the entrance and growth of the ice far from the entrance section. At water temperatures above 1°C we found only sickle-shaped ice profile in the experimental pipe section.

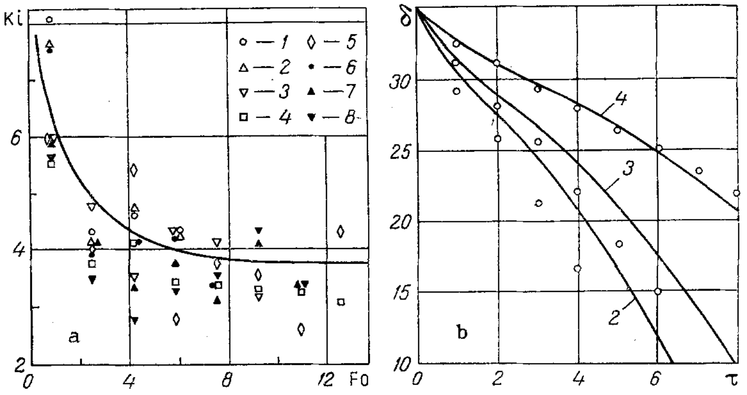


Fig. 3. Time dependent change of the Kirpichev number (a) (solid line: calculation after [3], dots: experimental data for experiments Nos. 1-8, respectively) and of the mean radius of the liquid phase (b) in the section 568 mm from the entrance to the pipe. The numbers next to the curves indicate the number of the experiments. δ, mm; τ, h.

On the basis of the experiments it was established that the thermal front from the pipe downward, from the instant that water was let into the pipe, reached the zone of melted soil after 5-10 h, and only in experiments with water of more than 1°C. In other experiments the thermal front from the pipe did not manage to get as far as the zone of the melted soil, and this enabled us in subsequent calculations to regard the soil massif as semiinfinite.

For laminar flow of water ($Re < 2300$) and for a concentric ice profile we calculated the heat flux from the pipe wall to the soil, and then we found the Kirpichev number. The heat flux expended on ice formation was determined from the layer of ice forming in the pipe within one hour. The thermal flux from the water to the ice was found according to [5]. In Fig. 3a a comparison is shown of the experimental data according to Kirpichev number with those calculated according to [3] in dependence on the Fourier number. When the experimental data were compared with the method of [3], we used as initial heat capacity the effective heat capacity that was calculated according to [6] taking the bound moisture (nonfrozen water) into account. It can be clearly seen from Fig. 3a that the higher the soil temperature and the temperature of the water supplied to the pipe, the more unstable is the process of ice formation and heat exchange itself. The thickness of the ice forming inside the pipe is strongly dependent on the soil temperature and on the temperature of the water supplied to the pipe. The growth rate of the ice for different soil temperatures is given in Fig. 3b. The same figure also contains lines showing the growth of ice calculated by the method of [3]. It can be seen from Fig. 3b that the method of thermal calculation of underground pipes transporting freezing liquids expresses qualitatively correctly the examined process at the starting period [3]. Only when the soil temperature is very low is there a substantial divergence of the theoretical data from the experimental ones across the thickness of the forming ice. In our opinion, the main cause of this deviation is the fact that Krasovitskii [3] did not take the effect of the surface of the earth on the lower half of the pipe circumference into account.

NOTATION

$Ki = q_l/\lambda_\varphi(t_T - t_0)$, Kirpichev number; q_l, linear thermal flux; t_T, mean pipe wall temperature; t_0, soil temperature on the axis of the pipe placement far from the pipe; $Fo = a_{so}\tau/R_2$, Fourier number; δ, mean radius of the liquid phase.

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JOINT DIFFUSION IN INTERSTITIAL SOLUTIONS

Yu. A. Buevich

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Within the framework of the simplest model of a two-component solid solution the article examines the dependence of the diffusion fluxes of implanted substances on their concentration and on the inhomogeneity of the lattice composition. It is shown that cross effects lead to contributions that are comparable in magnitude to the principal fluxes.

In the practice of thermochemical treatment of metals and alloys, and in particular in processes of case-hardening and nitriding, situations are ordinarily encountered where the introduction of an additional admixture to a system substantially changes the rate of mass transfer and the kinetics of saturation of the material with the principal diffusing substance. For instance, the addition of nitrogen is able to accelerate the transfer of carbon to more than twice the original rate, the same effect is found when a phase contains ammonia, methane, or some other gases (see, e.g., [1, 2]). Under certain conditions mass transfer is even possible in the direction of the gradient of concentration of the substance. Although the fundamental cause of such "ascending" or "negative" diffusion is not difficult to understand, e.g., on the basis of Darken's phenomenological theory [3, 4], such a strong effect of implanted admixtures on the diffusion of any of them still lacks of a physical explanation on the example of the simplest possible model. A physical analysis of this kind is carried out below for a two-component interstitial solid solution within the framework of an atomic model in which we neglect the existence of an electron subsystem and the deformations of the crystal lattice of a metal or an interstitial alloy; only the statistical configurational properties of the system and the interaction energy of pairs of atoms in the nodes and internodes of the lattice were taken into account.

We will assume that both kinds of interstitial atoms fill the same type of internodes forming a regular lattice with the coordination number γ, and that each internode borders on z nodes of the basic crystal lattice which may be free (with a probability $m_V = M_V/M$) or filled with J various types of atoms (with the probability $m_j = M_j/M$, $j = 1, \ldots, J$). We assume that the composition of the alloy, i.e., the numbers M_j and M_V, are known and that they do not change during the process of diffusion. This last corresponds to the assumption that the diffusion coefficients of interstitial atoms are much larger than these coefficients for vacancies and atoms in the nodes of the basic lattice.

We represent the interaction energy of the interstitial atoms between each other and with the atoms in the nodes per unit volume in the form

$$E = \sum_{j=1}^{J} (\varepsilon_1^j M_{1j} + \varepsilon_2^j M_{2j}) + \varepsilon_{11} N_{11} + \varepsilon_{12} N_{12} + \varepsilon_{22} N_{22}, \quad (1)$$

where M_{ij} is the concentration of bonds of interstitial atoms of i-th type with atoms of j-th type in the nearest nodes; N_{ik} is the concentration of bonds of interstitial atoms of the i-th and k-th types in the neighboring internodes. Formula (1) corresponds to the approximation of the nearest neighbors.

A. M. Gorky Ural State University, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 6, pp. 974-979, June, 1986. Original article submitted July 19, 1985.

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