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EXPERIMENTS WITH SUPERCOOLING AND ICE FORMATION IN FLOWING WATER

BY TORKILD CARSTENS

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Summary. This paper describes some cold-room experiments in which a body of water was agitated so as to prevent thermal stratification and the subsequent formation of an ice cover. The stirring led to an essentially uniform cooling of the entire mass of water. This supercooling and its subsidence was the subject of our study.

Our experiments showed that the supercooling of water of the same quality was a function of the rate at which heat was lost from the free surface and of the rate at which the flow could transport this heat to the water surface.

Although our findings are neither very surprising nor entirely novel, their engineering significance has — to the author's knowledge — not been clearly spelled out before. The implications for ice engineering, in particular the construction of river intakes, may well be a re-evaluation of present design practice.

1. Introduction. The practical problem leading up to this investigation is that of intakes in rivers with an ice regime. Whether such intakes are designed for large quantities of water such as in hydro-power schemes or for smaller discharges such as in domestic water supply systems, their proper functioning is threatened by ice. Several early, now deserted hydro-power plants, in Norway and other countries, testify to the difficulties in maintaining open river intakes throughout the cold season.

In a river ice may form not only at the free surface as in a reservoir, but equally well at any fixed boundary exposed to the flow. More important still, it may form anywhere within the water mass as freely floating crystals, frazils.

Each reach of open river has its characteristic ice. The ice discharge passing any cross-section is a mixture of ice from all open reaches upstream. Depending on the physiography of the river, all, some, or only one of the following categories of ice may be present at the same time:

1. Solid sheet ice floes of high density, originating from an ice cover;
2. Less solid and less dense ice floes representing advanced stages of metamorphosis either of melting sheet ice or of freezing frazils;
3. Clusters and floes of loose ice, representing early stages of metamorphosis of frazils, or trapped snow;
4. Frazils, freely floating crystals of freshly formed ice.

The two major hazards to a river intake are

A. Accumulations of ice in front of the intake, and
B. Withdrawal of too large concentrations of ice through the intake.

The larger and denser the ice floes are, the more easily they may form bridges across the river or its gated section and cause ice jams. On the other hand, the smaller and looser the ice clusters are, the more easily they are drawn through the intake.

In discussions of the latter hazard DEVIK has introduced the catch phrases 'active ice' and 'passive ice' to distinguish ice surrounded by supercooled water from ice surrounded by water at its freezing point. The former ice has a much greater tendency to stick to submerged objects than the latter. Any hydraulic structure can function without difficulties until the concentration of ice in the flow exceeds a certain limit. If the ice is active, however, this limit is only a fraction of the permissible concentration of passive ice.

The primary purpose of our cold-room experiments was to find out what affects the water temperature significantly, or, more specifically, the supercooling of the water. The next step in our investigation will be to explore the possibility of applying the laboratory results in the field.

Based on our judgement of the engineering problem and our means of tackling it, we selected three variables for study:

1. The quality of the water from the point of view of nucleation, that is, the concentration of suspended solids in the water;
2. The rate of heat loss through the free water surface;
3. The quality of the flow from the point of view of crystal growth, that is, the capacity for heat transfer by turbulent diffusion.

Earlier investigations. The latent interest in ice in northern countries has been intensified in the past by major calamities due to ice or by major construction projects involving estimation of the risk of such calamities.

Characteristically, the upsurge in Russian ice research was precipitated by the complete clogging of the water supply system for the city of Leningrad in 1914. The measurements of supercooling in the Neva and other Russian rivers enabled ALTBERG (1936) to explain the formation of anchor ice as due simply to heat convection. He thus settled the age-old discussion on the paradox of bottom ice and went on to perform an extensive series of experiments on supercooling. Altberg and his collaborators investigated both the nucleation process and the rate of crystal growth. They became strong advocates of the heterogeneous or complex theory of nucleation, which presumes the adsorption of water molecules on solid surfaces.

Significant Canadian contributions were caused by the first St. Lawrence Seaway project (1914). The book by Barnes (1928) supported certain ideas on nucleation and on radiation that have since been proved wrong. Unfortunately, these misconceptions have shown a remarkable persistence.

Devik (1931) reported his observations of supercooling in still and flowing water in nature. Of particular interest were the low surface temperatures he was able to measure in sheltered patches of open water surrounded by ice.

While the crystal growth had been given a satisfactory explanation, the nature of nucleation was still debated when Dorsey (1948) summed up the accumulated experience. He was able to discard the so-called homogeneous theory, which allows nuclei to form in pure water.

Ten years later, Mason (1958), on the basis of new and better experiments, reexamined the nucleation process and came out in support of both the homogeneous and the heterogeneous theory of nucleation.

However, since the probability of homogeneous nucleation is extremely small until the supercooling approaches 40°C, this event can be ruled out of our discussion. For heterogeneous nucleation Mason discovered a high correlation between the structure of good nucleating crystals and that of ice crystals.

Prediction equations for water temperatures, based on estimates of the heat exchange between the water surface and the atmosphere, have appeared regularly and are now numerous. In principle they are similar to other formulae describing a heat balance, such as for evaporation from water or ground, snowmelt, etc. The chief mechanisms of heat transfer are radiation, convection, and evaporation. As they are all local functions of the micro-climate, it is not surprising that there are many heat loss formulae.

2. Experiments. *Experimental setup and procedure.* The experiments were conducted in a cold room at the Refrigeration Department at the Technical University of Norway. The room temperature can be lowered to $-30°C$, however, most of the tests were carried out at $-10°C$.

The experimental flume has the shape of a track race and is shown in Fig. 1. Each straight section is 400 cm and each curve 200 cm long. The width of the flume is 20 cm and the height 30 cm. The still water depth was kept at 20 cm, giving a water volume of 480 litres.

At the beginning of one curve there is a propeller, slightly reset in the bottom to prevent air entrainment through a vortex. With the propeller operating, flow velocities of 70 cm/s are obtained. The velocity distribution is not as even as in rectilinear flow; on the other hand, it is surprisingly uniform at the end of the straight sections. The point measurements of velocities were made with a miniature current meter at ordinary

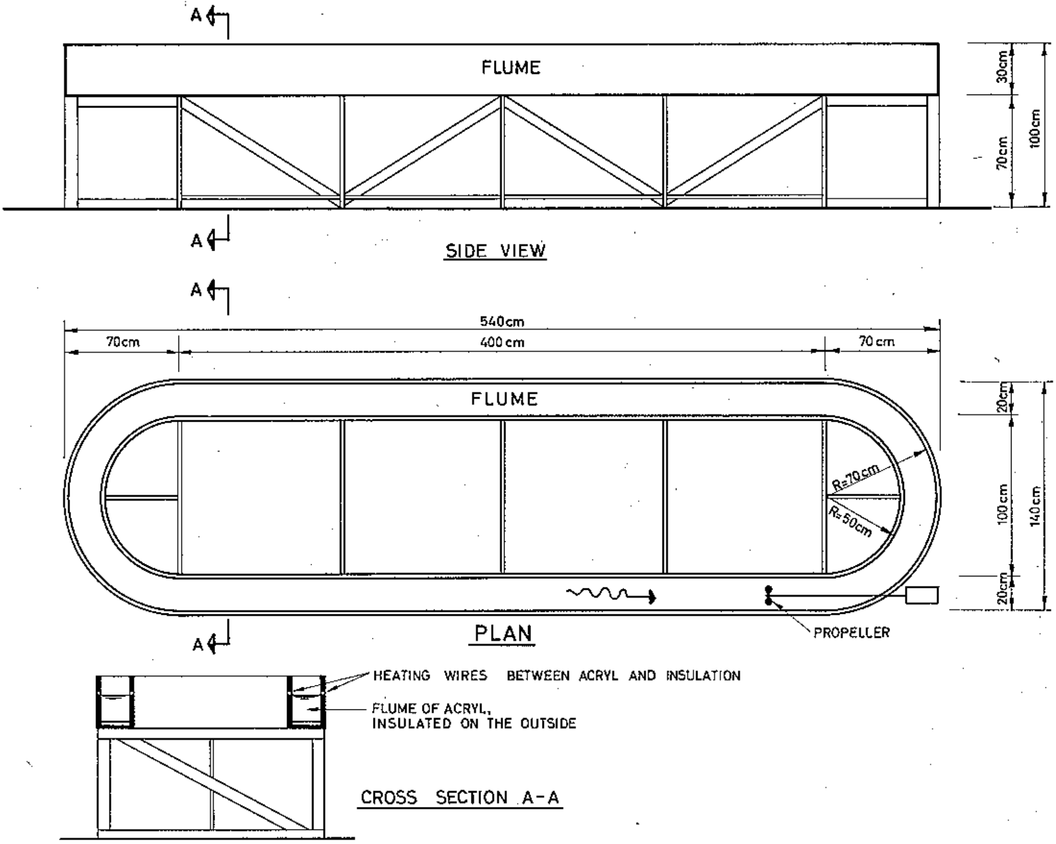

Fig. 1. Recirculating flume for ice experiments.

room temperature. In supercooled water only observations of surface and average velocities, by means of floaters and drifters, were made.

The flume bottom and sides are insulated, thus heat losses from the free water surface are predominant. A fan can direct an air stream along one of the straight sections. Maximum air speed measured 6 cm above the water surface is 3.0 m/s.

Water temperatures were measured with a hand-held mercury thermometer marked to 0.01°C and readable to 0.002—0.003°C.

All recordings were taken with the thermometer in the same position, with the bulb immersed 5—10 cm. Occasionally ice formed on the thermometer and the bulb had to be removed. Any trace of ice on the bulb raised the thermometer temperature beyond that of the flowing water.

The vertical temperature gradient that must exist in the flow was too small to be detected with the thermometer when the propeller was on. With the propeller off an interesting situation arose in the flume: While cooling through the free surface promoted

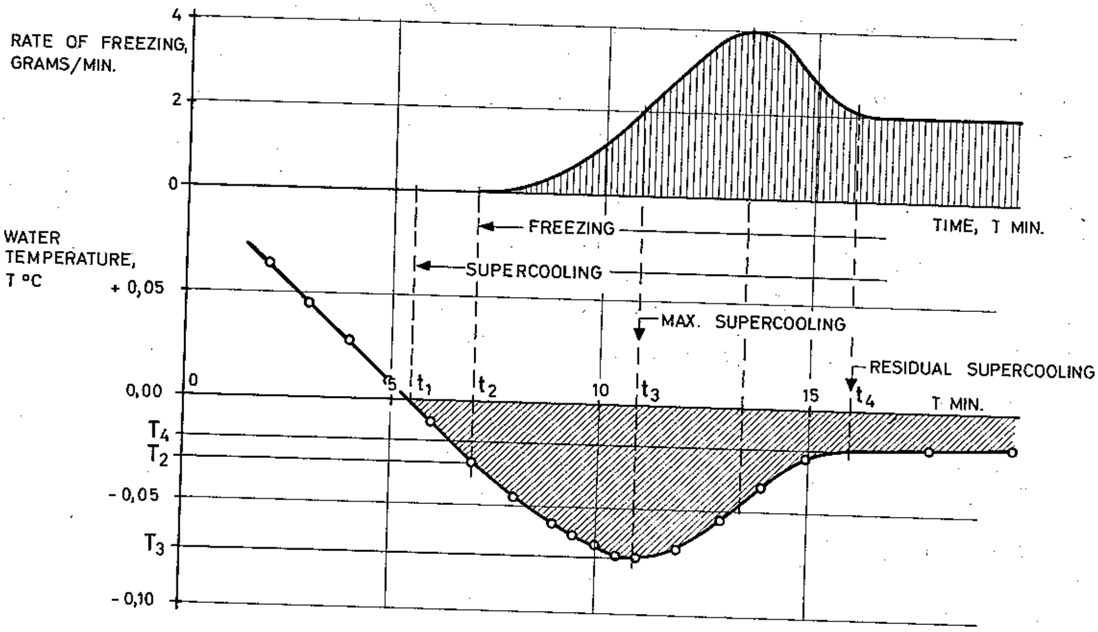

Fig. 2. Typical time history of supercooling.

thermal stratification in the decaying flow, heating at the ice-covered surface counteracted stratification by setting up a natural convection. As a result a weak, vertical temperature gradient was observed for a while in the flume, only to disappear after a full ice cover had developed.

In the beginning ice always formed first on the propeller and caused a reduction of the flow velocities. This source of error was all but eliminated after the propeller was equipped with a small heating element.

Time history. A typical time history of an experiment is shown on the lower curve of Fig. 2, where the water temperature T(°C) is plotted as a function of time t. To begin with, the water temperature decreases linearly with time, indicating a constant rate of heat loss. At time t_1 the water temperature reaches the freezing point, and beyond time t_1 there is supercooling. At time t_2 the $T-t$ curve starts to deviate from the straight line. Since the heat loss is constant, this means that the first ice crystals have formed and released the liquid's latent heat of fusion.

Once started, the growth of ice crystals accelerates. At time t_3 the water temperature reaches a minimum T_3, indicating a balance between released latent heat and heat loss. Between time t_3 and t_4 the water temperature rises, indicating an excess of released latent heat over the heat loss, until at time t_4 most of the supercooling has disappeared. From time t_4 on the water temperature T_4 remains essentially constant, and this means that the released latent heat exactly equals the heat loss.

Thus the characteristic $T-t$ curve, after crossing the freezing point as a straight line, levels off to reach a minimum temperature, i.e., a maximum supercooling, of T_3°C. The curve then rises to a constant temperature T_4 which is lower than the freezing point and represents the residual supercooling, T_4°C.

The upper curve of Fig. 2 shows the rate of freezing, dMi/dt, which is derived from the lower curve $T(t)$ by the formula

$$\frac{dMi}{dt}=\frac{1}{L}\left(cM_w\frac{dT}{dt}+Q_s\right) \tag{1}$$

in which L is the latent heat of fusion, c the specific heat of water, M_W the mass of water, Q_s the rate of heat loss from the water surface.

Visual observations. The first ice crystals, the frazils, became visible at time t_2. These disk-shaped crystals had diameters as large as 2—3 mm and showed up anywhere in the liquid. The frazils increased rapidly in numbers, but not in size, until shortly after time t_3 the formerly clear water became more or less opaque. Then — probably through collisions — flocs formed that were large enough to gravitate towards the surface, and the water soon became clear again.

The flocs formed clouds and clusters that were still to a large extent suspended in the flow, but now with a high concentration near the surface and very small amounts near the bottom. From time t_4 on, only a gradual thickening of the slush layer near the surface was observed.

Quality of the water. In the first phase of the investigation on supercooling we observed the effect of adding solids to the flow.

The quality of the tap water in the flume was first tested without any added solids, under conditions that were later kept constant: The propeller motor was going at full speed, which gave the 480 litres of water in the flume an average velocity of 60 cm/s. The air temperature was maintained at -10°C, giving a cooling rate of 0.01°C/min.

Time histories of repeated runs — after remelting of the ice — were identical and showed a maximum supercooling of 0.04°C. The residual supercooling, not considered significant for the problem, was hardly observable.

Sand of various grain sizes and densities was added in different quantities and also in different ways to the flow.

Sand of normal grain density 2.7 did not have much effect on the supercooling. However, an Icelandic lapilli, a sand with less than normal density, did reduce the maximum supercooling significantly.

The turbulence of the flow was sufficient to suspend only the smallest sand grains, so the bulk of the sand moved slowly as bed load. Of the lapilli more was suspended; but in spite of the larger suspended volume, the turbidity of the flow was less with the lapilli than with the sand.

If the quality of the water was really involved, we think the turbidity would be the decisive factor. A high turbidity indicates the presence in the flow of dispersed solids with a large total surface to promote nucleation.

The results or our experiments with sand and lapilli were such that we doubt the suspended solids affected appreciably the quality of the water. It seems more likely that the presence in suspension of large grains influenced the quality of the flow. Our attempt to correlate the concentration of solids to the nucleation crisis was therefore abandoned.

However, since our basic approach was a utilitarian one, we proceeded to try out ideas on how to reduce supercooling on a large scale by adding inexpensive and readily available granulates to the flow. This first experimental phase was therefore brought to an end with a test series in which floating matter — large grains of lapilli, sawdust, and snow — was tried out (TESAKER 1966).

In all cases substantial reductions of the maximum supercooling were observed. The great difficulty with such experiments is that there is no immediate way of extrapolating the laboratory observations to the full field scale, as none of the three independent variables of the freezing problem remain constant.

In the subsequent experiments a constant water quality was secured by remelting the ice and reusing the same water.

Rate of cooling. The experiments with the rate of cooling as parameter were carried out in a small tank with insulated walls and bottom. A constant circulation was maintained in the tank by means of a propeller. The cooling was chiefly by convection from the free water surface to the $-10°C$ air stream above, created by a fan. The rate of heat loss was varied simply by varying the distance between the tank and the fan and thereby the air speed near the water surface.

The observations quite consistently showed that the higher the cooling rate, the lower the temperature became before ice formed. Fig. 3 shows on the same graph the $T-t$ curves for six experiments with different rates of cooling. The curves are plotted so that the times at which the water temperature is exactly 0°C coincide, in order to make comparisons easier.

All curves have the general shape shown on Fig. 2. The influence on the water temperature of an increase in the rate of heat loss through the free water surface is seen to be that

A. the maximum supercooling increases,
B. the residual supercooling increases,
C. the rise from maximum supercooling to residual supercooling requires less time.

The water temperature at the beginning of these tests was well above freezing. Fig. 4 shows the results of the superposition of two tests, that is, an experiment in which a change in the rate of cooling was made without first heating the water and melting the ice.

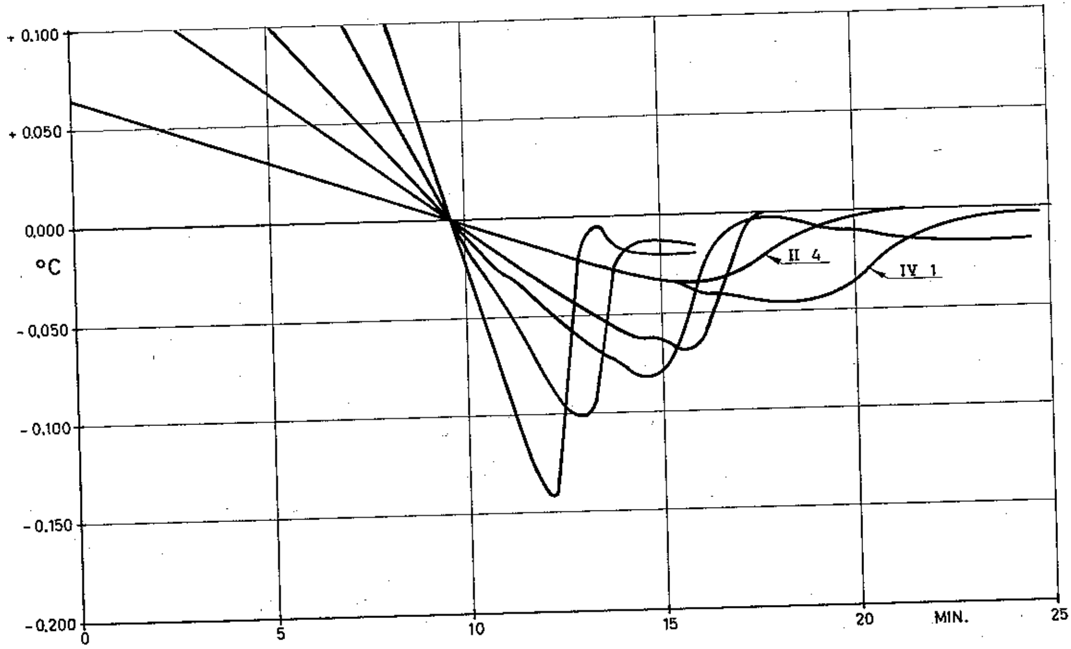

Fig. 3. Effect of rate of cooling on supercooling.

The cooling rate was, to begin with, 0.8°C/min; and the same sequence of events was observed as described above. After an apparently steady state was reached with a certain residual supercooling, the cooling rate was increased about ten times. The water temperature dropped off again, to reach a lower minimum than before, then rose to a new residual supercooling, also a lower temperature than before.

Quality of the flow. The next step in our investigation was to measure the supercooling for various modes of flow, obtained by simple mechanical devices. As stated earlier, the essential quality of the flow in regard to ice formation is the capacity for heat transfer. Accordingly, both convection and diffusion become important. Especially the latter is extremely difficult to evaluate quantitatively in water, and the presence of ice certainly does not make it any easier. No attempt has been made to determine the heat transfer properties of our experimental flows.

Tank tests. In the tank used for the cooling rate experiments a qualitative change of the flow was made, and the effect of this change on the supercooling was observed.

First a test was run with the propeller operating, and the $T-t$ curve A on Fig. 5 was obtained. This is the curve for a 'strong' turbulence, with a systematic motion as well, caused by the propeller slipstream. The result is similar to those of the previous tests with the propeller operating.

In the next test the propeller was not operating. This time the motion was imparted

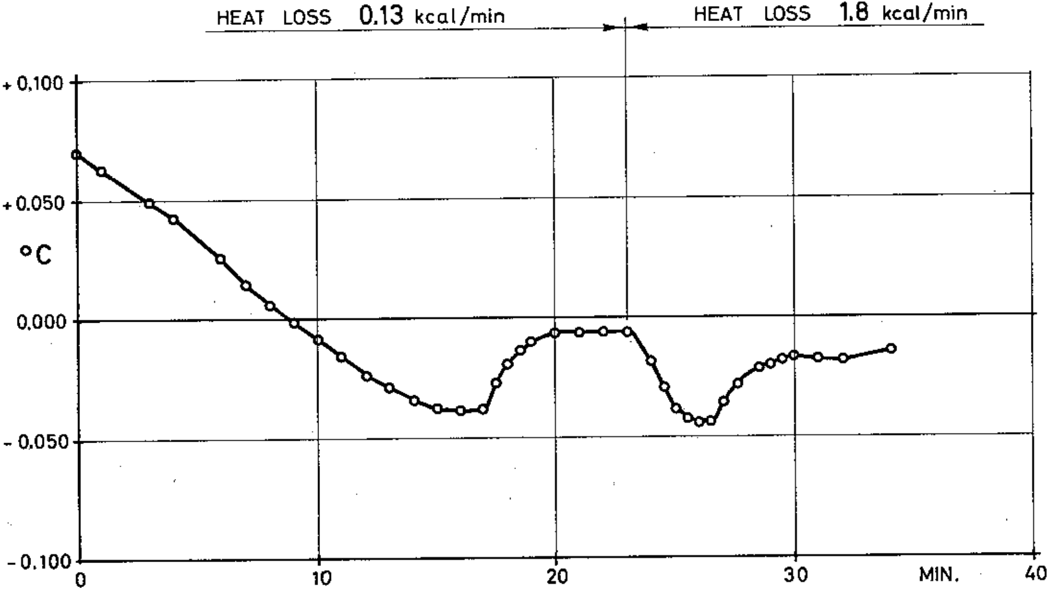

Fig. 4. Effect of change in rate of cooling on supercooling.

to the water by the tank itself oscillating at 50 cycles per second with a small amplitude. The oscillations were caused by a vibrator placed on the table that supported the tank. The cooling rate was the same as in the previous test. Upon reheating the water to melt the ice, no changes were made other than to start the vibrator instead of the propeller, to obtain a 'weak' turbulence in the tank.

The 'weak' turbulence test result is shown as curve B on Fig. 5. The difference in performance between the 'weak' and the 'strong' turbulence tests is striking. While the 'strong' turbulence only permitted the water to reach a minimum temperature of −0.04°C after some 6—8 minutes of supercooling, the weak turbulence permitted the water to reach −0.1°C after about 30 minutes of supercooling.

The subsidence of the supercooling was equally at variance. The strong turbulence raised the temperature rapidly to a residual supercooling very close to 0°C. The weak turbulence raised the temperature very gradually to −0.03°C within about 30 minutes. At this point the propeller was started, which resulted in an almost repeat performance of the last phase of the previous propeller test.

Flume tests. In the flume shown in Fig. 1 the $T-t$ curve A of Fig. 6 was obtained while the water in the flume was driven by the propeller at a speed of about 50 cm/s. Curve A looks rather like dozens of others that we have observed under similar conditions of propelled flow, or flow with a strong turbulence.

The curve shows a minimum temperature of −0.06°C after four minutes of super-

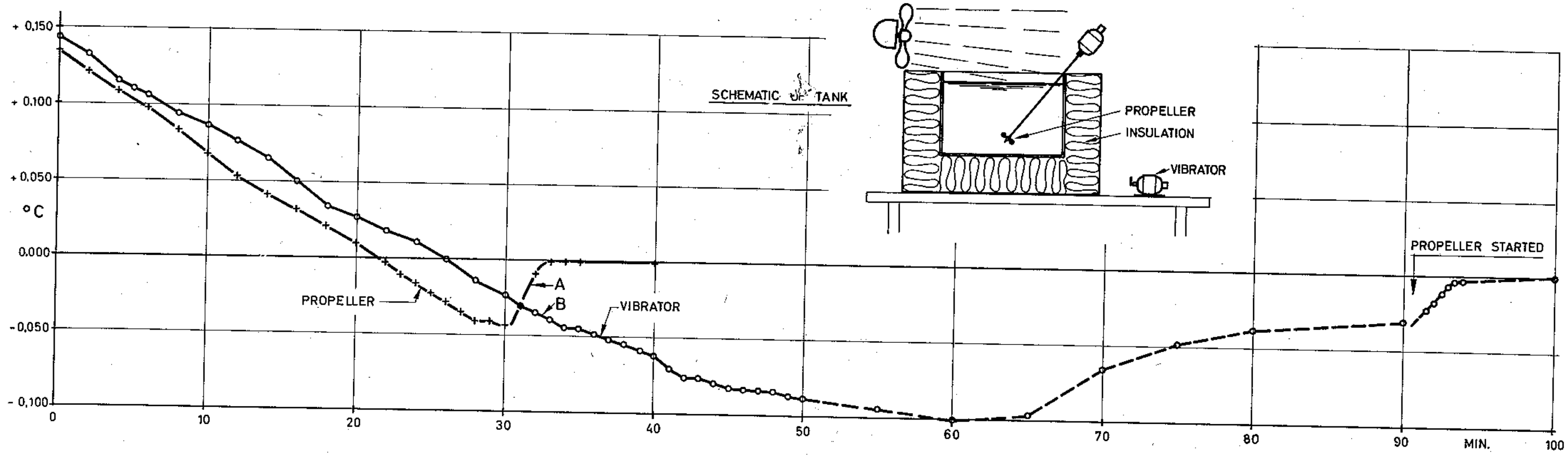

Fig. 5. Effect of turbulence on supercooling.

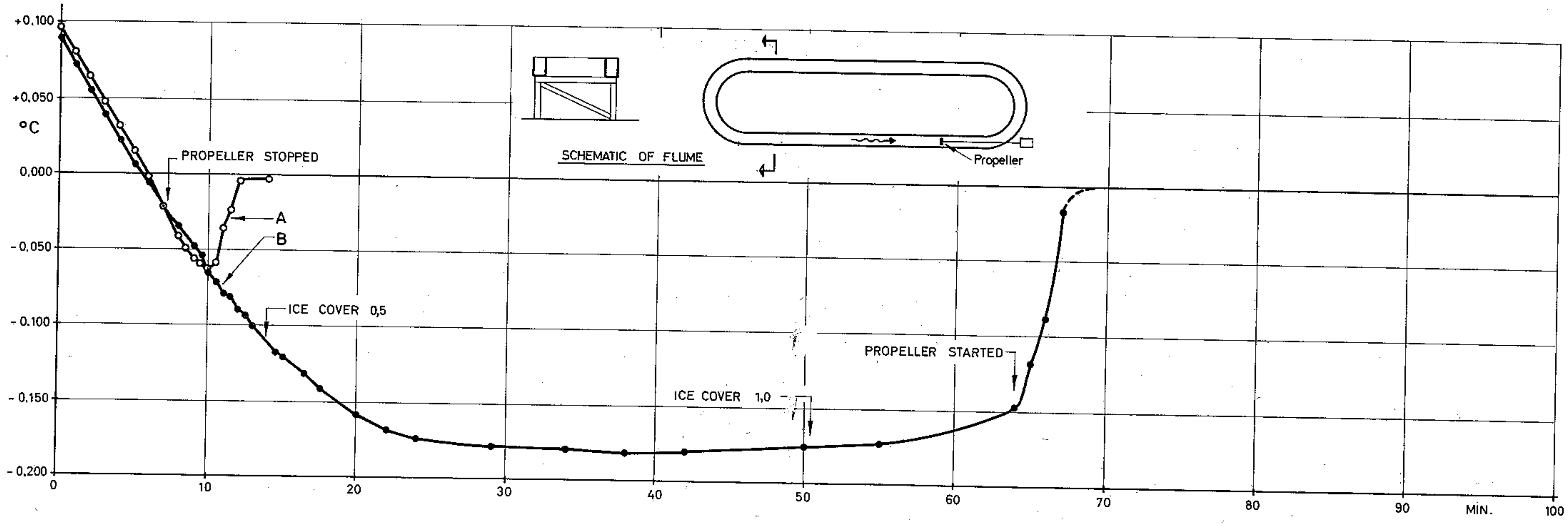

Fig. 6. Effect of turbulence on supercooling.

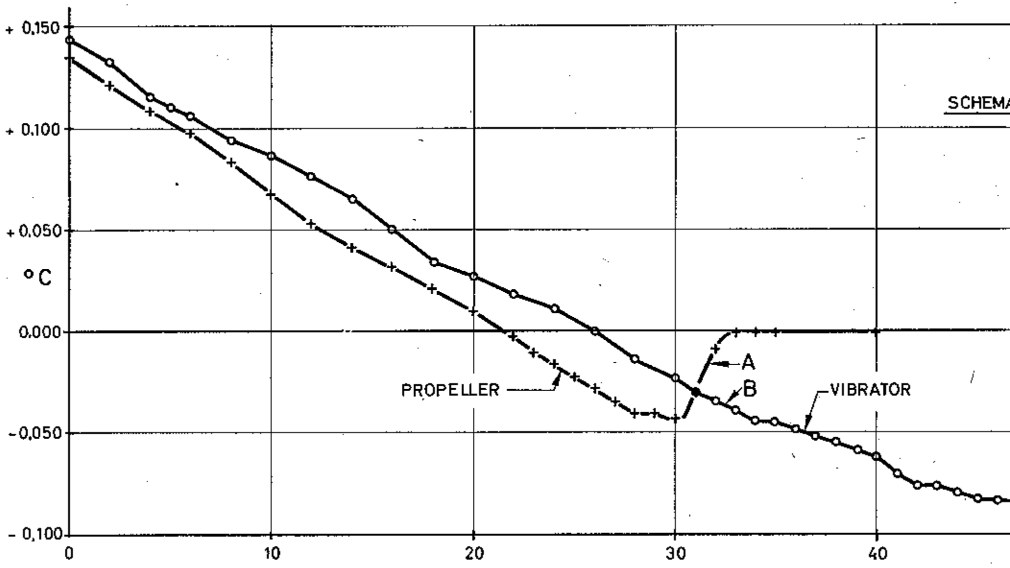

Fig. 5. Effect of t

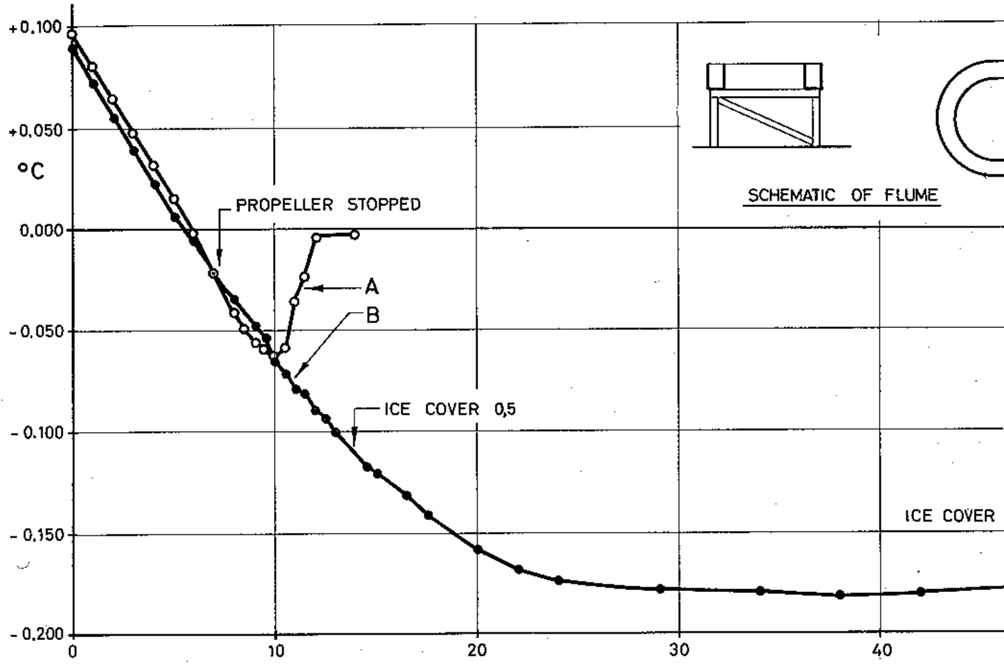

Fig. 6. Effect of t

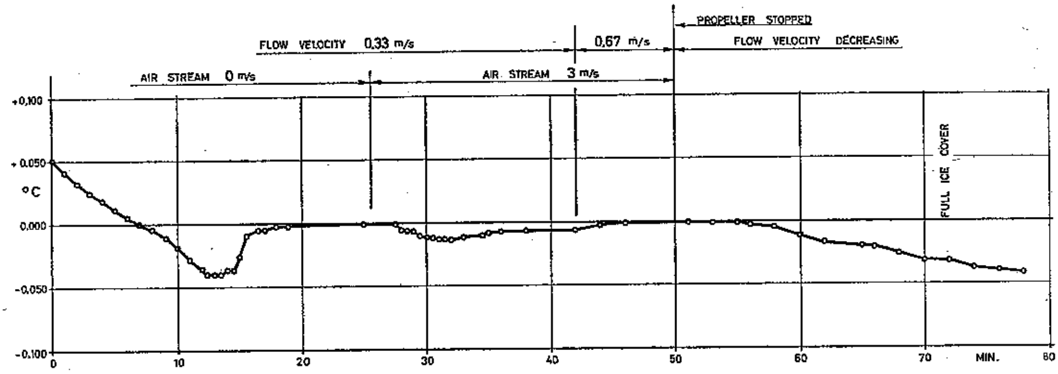

Fig. 7. Time history of supercooling with many parameter variations.

cooling, followed by a rapid rise to a few thousandths of a centigrade residual supercooling.

The next test started out exactly as the one giving curve A, but this time the propeller was stopped after one minute of supercooling. From that moment on the water coasted along, driven by its own inertia and resisted by the wall friction. The flow therefore gradually lost its speed, while the turbulence decayed.

The time history of the water temperature for this decaying flow is shown as curve B on Fig. 6. A minimum of −0.18°C was observed after about 30 minutes of supercooling. After another 30 minutes the temperature had climbed to −0.15°C. Now the propeller was started, and within 3 minutes the temperature jumped almost to the freezing point.

Crystallization started shortly after the supercooling had begun, so the water surface gradually became covered with ice. After about 10 minutes of supercooling some 50 per cent of the water surface was covered with thin ice. For the last 15 minutes of the test a very slow and strongly supercooled flow prevailed under a 100 per cent ice cover.

The rather striking observation that a supercooled flow can survive for a long time below an ice cover was substantiated in several similar experiments. The rather self-explanatory time histories of two of these tests are shown on Figs. 7 and 8.

Fig. 7 demonstrates the influence of a succession of flow conditions and heat loss rates. The beginning is similar to curve A on Fig. 6. An increase of the heat loss after 25 minutes drives the temperature down again, but only slowly since so much of the water surface is covered with ice. After a transient period the new residual supercooling, corresponding to the increased heat loss, is obtained.

After 42 minutes the flow velocity is doubled, from 33 cm/s to 67 cm/s. The increased turbulence cuts the residual supercooling below the observable limit.

Finally, after 50 minutes, the propeller is stopped. As the turbulence decays, the temperature is forced down, until at the end of the test, after 78 minutes, the supercooling is 0.04°C.