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EXPERIMENTAL STUDY OF FREEZING AND MELTING OF FLOWING WARM WATER AT A STAGNATION POINT ON A COLD PLATE

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TECHNICAL PAPER proposed for presentation at
Fourth International Heat Transfer Conference
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Abstract

A jet of warm water was directed against a cold surface producing in the vicinity of the stagnation point a uniform convective heat transfer coefficient. By providing transient cooling of the surface, a layer of ice could be made to form on it or an existing layer to melt. The ice thickness variation with time was measured and compared well with a transient analysis carried out for a convective boundary condition at the solid-liquid interface. The convective heat transfer coefficient was determined experimentally at steady state conditions. The analysis predicted the transient solidification adequately for engineering applications.

INTRODUCTION

There are many engineering applications where freezing or melting occurs in a flowing liquid. Some examples are: freezing of rivers, solidification of a flowing liquid metal in continuous casting processes, and freezing in heat exchangers in which the flowing coolant is at a temperature below the freezing point of the flowing warm liquid that is being cooled. In these applications heat is convected from the warm flowing liquid to the frozen layer-liquid interface. During the freezing process, this convective heat combines with the latent heat of fusion that is released at the interface and is conducted through the growing frozen layer to the cold surface. During a melting process, a part or all of the convective energy from the warm liquid supplies the energy to melt the frozen layer. The remainder is transferred through the frozen layer to the surface.

In reference 1 we developed a calculational method for predicting the growth of a frozen layer in a warm flowing liquid. The layer formed on a plane wall that was convectively cooled from the opposite side. The bulk temperatures and the convective heat transfer coefficients of the warm liquid and the coolant were assumed to be unchanging during the growth period. The heat flow was assumed to be spacially one-dimensional. This model was tested experimentally in an apparatus where chilled alcohol flowed over one side of a thin flat metal plate and warm water flowed over the other side. Measurements were made of the ice layer thicknesses during the growth period and these compared well with the calculated thicknesses.

The present study was initiated to provide additional experimental information on freezing in flowing liquids. In reference 1 the water flow was restricted by the equipment to being laminar over the test section, and it was desired to extend the data into the turbulent range to see if this would have any influence on the freezing process. In reference 1 the convection on the water side was of the flat plate boundary layer type providing a heat transfer coefficient that decreased with position along the flow direction. This produced an ice layer that increased in length along the plate and introduced some uncertainties as a result of two-dimensional heat conduction in the ice layer and the plate on which it formed.

For these reasons, and to study freezing in another configuration, a new apparatus was designed utilizing liquid flowing at a stagnation point. Near a stagnation point the convective heat transfer coefficient is constant, which would lead to the formation of a flat one dimensional frozen layer. The apparatus was designed so that high flow rates could be obtained producing turbulent heat transfer at the moving solidification interface. Transient measurements of ice formation were made for both freezing and melting. These are compared with a one-dimensional analysis incorporating convective heat transfer at the solidification front.

A survey of related literature is given in reference 1, and will not be repeated here.

SYMBOLS

C_p	specific heat of frozen material
h	convective heat transfer coefficient
k	thermal conductivity of frozen material
L	latent heat of fusion
S	dimensionless parameter, $C_p(t_f - t_w)/L$
t	temperature
$\bar{t}$	mean temperature in frozen layer
X	thickness of frozen layer
ρ	density of frozen layer
τ	time from start of transient

Subscripts

f	at freezing temperature
ℓ	liquid phase of freezing material
w	at wall

APPARATUS

Water Flow Loop

The water flow loop (Fig. 1) was a sealed system in which the water could be deaerated with a vacuum pump and then placed under a helium cover. This was done to eliminate the trapping of air bubbles within the ice, which could influence the ice thermal conductivity. The water passed through a copper coil immersed in a water bath. By this means the water temperature was kept constant during each transient test.

Test Section

The test section, Figure 2, consisted of a clear cylindrical lucite flow chamber that contained: (1) the jet inlet and water flow outlets; (2) a bakelite plate against which the water jet impinges; (3) cylindrical inconel inserts imbedded in the bakelite plate at the stagnation point of the jet; (4) a copper plug and a brass cooling fin soldered to the lower end of the cylindrical inserts; (5) a dewar of coolant, liquid nitrogen or dry ice - alcohol mixture; and, (6) a thermocouple probe for measuring the ice layer thickness.

The cylindrical insert of inconel served as the heat transfer medium through which the convective heat from the water and the heat of solidification was removed. The insert was made of three concentric parts. The center plug was the important heat transfer element of the test section and was instrumented as a heat meter to obtain steady state heat fluxes, and to measure the transient surface temperature. The two concentric hollow cylinders shielded the center plug so that the heat conduction through it would be one-dimensional and the ice layer growing on it would be of uniform thickness at each instant.

Temperature measurements

All temperatures were measured with chromel-constantan thermocouples 0.0076 cm in diameter. Two surface thermocouples on the inconel center plug were each imbedded in a groove 0.0178 cm wide and 0.0127 cm deep and four thermocouples were soldered on the surface. These six couples were used to determine the degree of uniformity of the inconel surface temperature. The thermocouples along the length of the center plug were inserted into 1.4 cm long radial holes, which were drilled to accept 0.051 cm diameter, two wire, ceramic insulators. The free stream water temperature was measured with the ice thickness thermocouple probe and checked with another thermocouple inserted into the inlet water pipe.

At steady state the inconel plug was used as a heat flow meter. The plug was machined from a bar whose thermal conductivity had been calibrated. By knowing the conductivity and measuring the temperature gradient within the plug, the heat flow could be calculated. Inconel was used because it has a low conductivity for a metal. This provided fairly large temperature drops along the plug length which could be measured with good accuracy.

Ice-thickness measurements

The ice layer thickness was measured with a thermocouple probe developed in Reference 1. The thermocouple junction was made of 0.0076 cm diameter chromel-constantan wires that were butt welded and stretched between two needles mounted on a support. The support was held in a manually driven micrometer so that the junction could be positioned within 0.0025 cm of any desired height above the test plug surface. When the probe was in contact with the interface the probe output was very close to 0 mv. Thus, the position of the ice-liquid water interface could be located by noting the couple output and the micrometer position. The use during transient tests will be described in the next section.

Test Procedure

Prior to each transient the water flow rate was set, and the water temperature stabilized at the desired value by adjusting the bath around the water coil. These values were then maintained throughout the transient. The dewar of coolant was moved into position along the brass fin to provide the required cooling for the type of transient that was being studied. A transient freezing (or melting) test was initiated by quickly raising (or lowering) the dewar to a new height.

Several types of transients were studied:

(1) Start with no ice layer and then freeze to a steady state ice layer thickness.

(2) Start with a steady state ice layer and freeze to a thicker steady state layer.

(3) Start with a steady state layer and alternately melt and freeze, ending with a new steady state layer.

The position of the ice-water interface was measured during a freezing transient by positioning the thermocouple probe about 0.0127 cm above the initial interface location and allowing the ice to grow toward it. When the output of the probe registered 0 mv, the probe was quickly moved 0.0127 cm away from interface. During a melting transient, the probe was quickly moved toward the interface until the output registered 0 mv. The position of the probe and the time were then recorded. As the interface advanced or receded, the process was repeated thereby giving a succession of position-time readings.

When, in the case of freezing, a final steady state was achieved, or for melting there was an initial steady layer, all the temperatures within the inconel test plug were measured. This provided the steady state heat flow through the plug.

ANALYSIS

The analytical model used to predict the ice thickness variation with time is shown in Figure 3. During a transient the surface of the cooled plug varies with time. This is a boundary condition on the frozen layer at the plate. The other surface of the frozen layer is in contact with the flowing water. The question is: for a given wall temperature variation with time, will the ice layer freeze and/or melt as predicted by an analysis using the heat conduction equation in the layer and a conventional steady state convective heat transfer coefficient at the moving interface? If the measured growth does follow the analytical prediction this would show that there are no additional effects such as erosion or an alteration in the convective heat transfer coefficient taking place at the frozen interface.

In reference 2 solidification was analyzed for liquid flowing over a surface having a constant temperature. The quantity $S = C_p(t_f - t_w)/L$ governs the importance of heat capacity effects. In the present tests the $t_f - t_w$ was usually less than about 55° C so that S for ice was less than about 0.3. The results of reference 2 show that for S of this value, the frozen layer thickness at a given time is quite close to the case for $S = 0$. Thus in the analysis used for comparison with the present data the heat capacity term can be neglected, which results in considerable simplification.

A heat balance across the ice layer yields the following equation for the rate of change in the ice layer thickness, X,

$$h_\ell (t_\ell - t_f) + \rho L \frac{dX}{d\tau} = k(\bar{t}) \frac{(t_f - t_w)}{X} \tag{1}$$

where $\bar{t} = (t_f + t_w)/2$, $^{\circ}C$ and from reference 3

$$k(\bar{t}) = 2.25 \times 10^{-2} - 62 \times 10^{-6} \bar{t} + 1.15 \times 10^{-6} \bar{t}^2 \ \frac{\text{Joules}}{\text{cm sec } ^{\circ}\text{C}} \tag{2}$$

The thermal conductivity of the ice is thus taken instantaneously at the arithmetic mean ice temperature. At the ice-water interface $t_f = 0^{\circ}$ C = constant, and at the inconel plug surface, $t_w = t_w(\tau)$ is the measured time dependence of t_w. The initial conditions at $\tau = 0$ imposed on X and t_w were those measured in the experiment. Using these initial conditions and the measured $t_w(\tau)$ as a boundary condition, equation (1) was integrated numerically on a digital computer to yield $X = X(\tau)$ for each transient run. The h_ℓ was found from steady state tests as described in the next section. A comparison is then made with the measured $X(\tau)$ values.

RESULTS AND DISCUSSION

Two types of results were obtained from the measurements: those of the steady state heat transfer tests and those for transient melting and freezing. The steady state tests were to determine the heat transfer coefficients in the water at the ice-water interface and, for a bare plug, at the water-inconel plug interface. The steady state temperatures in the inconel plug and on the plug surface were measured. With these temperatures known, both the inconel plug and the steady-state ice layer could be used as heat flow meters.

Preliminary tests showed that a surface guard ring as shown in Figure 2 was helpful to maintain (1) flat ice layers of uniform thickness, and (2) one dimensional heat conduction through the ice during the transients. A flat guard ring of urethane insulation 0.254 cm thick was glued onto the bakelite surface shown in Figure 2. This ring insulated the edge of the ice layer and minimized the change in area of the ice-water interface during the transient growth period.

The steady-state tests with flat ice layers and with a bare plug resulted in values of heat transfer coefficients, h_ℓ, that were reproducible within 5 percent. The h_ℓ's evaluated from using the ice as a heat flow meter usually agreed within 5 percent with those evaluated from the temperature gradient in the inconel plug although in some instances differences as large as 10 percent were measured. Prior to running a series of transient tests, the flow rate and water temperature were fixed. Then by immersing the cooling fin to various depths in the dewar of coolant, various cooling rates were imposed. The steady state heat flows measured for each of the cooling conditions were used to compute the convective heat transfer coefficient in the impinging water. From these several measurements the average h_ℓ was calculated and used in the theoretical calculations to compare with the transient data.

The results for several transient tests are shown in Figures 4 to 6. For each test two curves and a set of data points are given. The dashed curve shows the measured temperature variation with time $t_w(\tau)$ at the surface of the inconel plug.

The predicted $X(\tau)$ is the solid curve and is compared with the measured thicknesses given by the data points.

Various types of transients were studied. In Figure 4 a transient is shown that begins from zero ice thickness and freezes to a final steady thickness. Figure 5 shows a transient that begins from an initial steady state layer and freezes to another steady layer. The small dip in the calculated curve is due to the fact that the average h_ℓ used in the calculation was slightly higher than the true value that actually existed. Figure 6 shows two tests where there is alternate melting and freezing.

An examination of the transient results shows that the theory accounts reasonably well for all the phenomena occurring in the solidification process. If the convective heat transfer is known, a freezing analysis with convection imposed in the ordinary manner at the interface will predict the frozen layer variation with reasonable accuracy for engineering situations.

CONCLUSIONS

Transient tests were made for solidification of warm water flowing over a cooled surface. The thickness of the frozen layer as a function of time was measured for conditions of freezing, melting, and alternate melting and freezing. The convective heat transfer coefficient from the warm water to the ice interface was measured at steady state conditions. This coefficient was then used in a transient analysis to compute the frozen layer thickness variation with time for various transient cold surface temperatures measured during the experimental transients. The predicted transient ice thicknesses agreed quite well with the observed values. This indicates that freezing in a flowing medium can be computed as a heat conduction problem with a moving boundary by using ordinary concepts of convective heat transfer at the interface.

REFERENCES

1. Savino, Joseph M. and Siegel, Robert: Experimental and Analytical Study of the Transient Solidification of a Warm Liquid Flowing Over a Chilled Flat Plate. NASA TN D-4015, June 1967.

2. Savino, Joseph M. and Siegel, Robert: An Analytical Solution for Solidification of a Moving Warm Liquid onto an Isothermal Cold Wall. Accepted for publication in International Journal of Heat and Mass Transfer, 1969.

3. Ratcliffe, E. H.: The Thermal Conductivity of Ice - New Data on the Temperature Coefficient. Philosophical Magazine, Vol. 7, No. 79, July 1962, pp. 1197-1203.

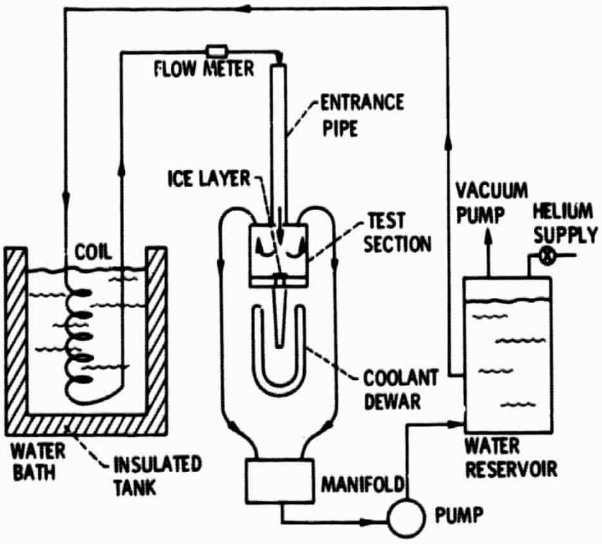


Figure 1. - Schematic of flow loop.

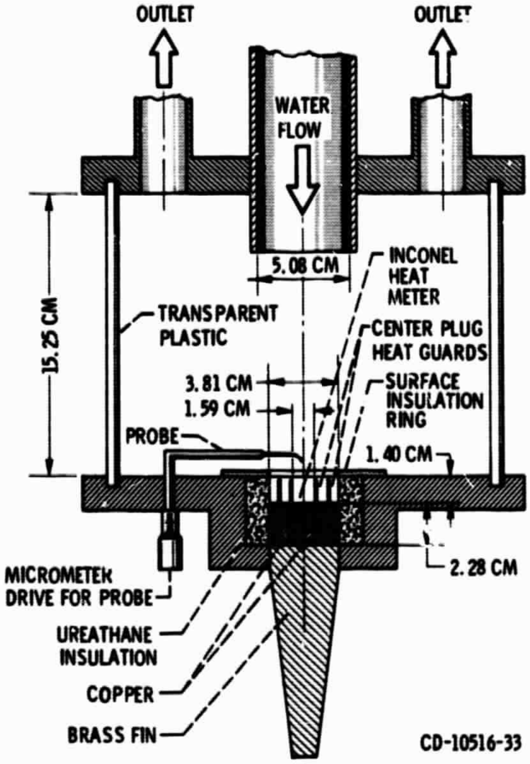


Figure 2. - Schematic sketch of test section showing the essential features.

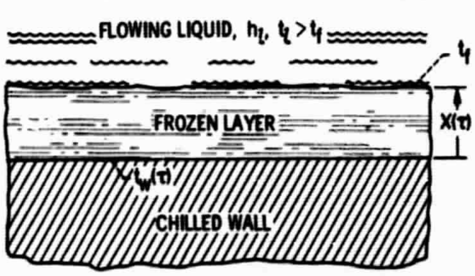


Figure 3. - Model of one-dimensional frozen layer formed in a flowing liquid on a chilled surface.

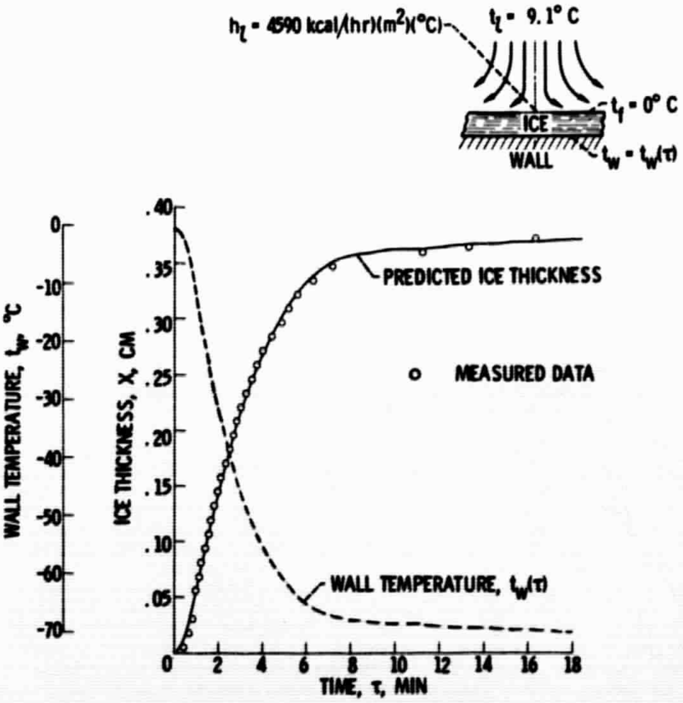


Figure 4. - Freezing of layer starting from zero initial thickness.

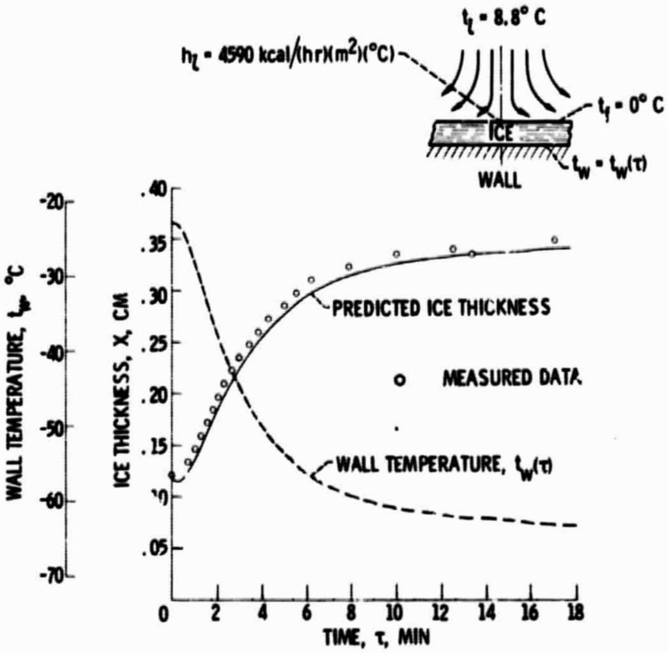
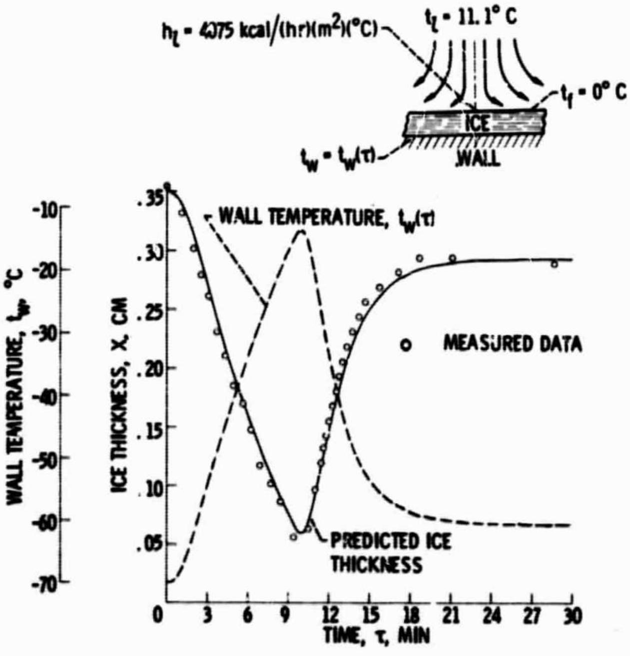
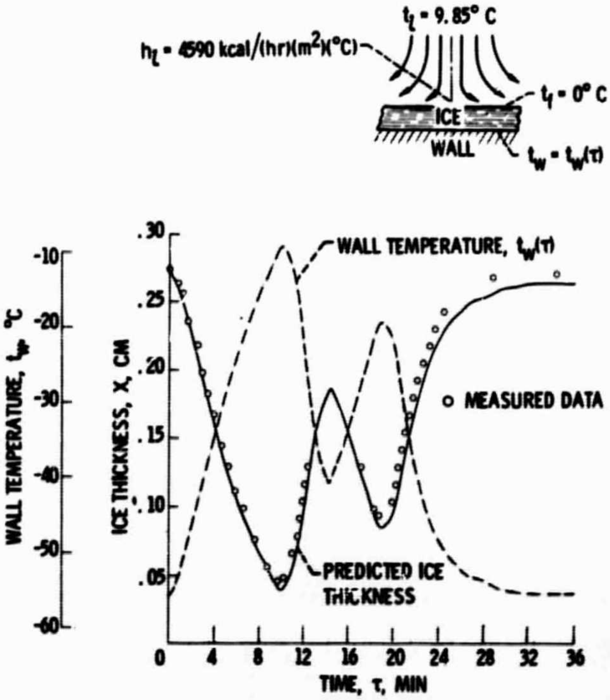


Figure 5. - Freezing of layer starting from finite initial thickness.



(a) One cycle.

Figure 6. - Alternate melting and freezing.



(b) Two cycles.

Figure 6. - Concluded.