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# Icing on submerged tubes: a study of occlusion

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**Abstract**—Theoretical predictions and experimental measurements are reported for the problem of ice formation on parallel, vertical tubes situated in a cross flow of cold water. The system has application to the damming of northern rivers. The results suggest that the theoretical model—which includes a description of occlusion—is capable of predicting ice growth over the range of conditions tested in the laboratory.

## INTRODUCTION

THE SUPPLY and control of water, so vital to the health and security of mankind, are no less important in northern nations with temperate climates than in tropical nations with arid climates; uncontrolled, excess water may be just as devastating as the total absence of water [1]. In many subpolar regions, and in the larger temperate zones, the spring thaw may bring about river flow rates and levels well in excess of the annual average, thus posing a short-lived but substantial problem in water management.

This paper is part of a systematic study—the Built Ice Veil Assessment (BIVA) Project—designed to explore heat transfer problems encountered during the construction of an ice 'dam'. The 'dam', more accurately called a veil, is proposed as a simple, inexpensive structure, easily and quickly built in remote locations in such a manner as to leave the river ecology intact [2]. The veil is not meant to be a complete or permanent man-made structure blocking the river, but a partial and temporary, natural structure whose sole purpose is to delay and control spring run-off.

Construction of the veil is begun by tapping the virtually infinite heat sink of the atmosphere during the winter period [2, 3]. A row of thermosyphons or heat pipes standing half submerged in the river acts to generate ice underwater, the growth around the lower part of each pipe continuing until it meets the growth around a neighbouring pipe. A series of parallel, vertical ice annuli gradually merge to form a continuous wall, as depicted in Fig. 1.

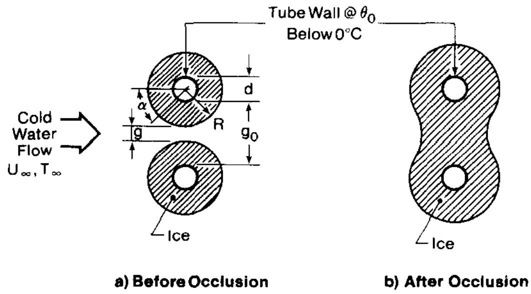


FIG. 1. Generation of an ice veil.

The rate of growth of the underwater ice is determined by the heat balance at the ice–water interface. The rate at which heat is conducted away through the ice will depend upon the temperature of the atmosphere and:

(a) the thermal resistance of the atmospheric convective system formed around the upper part of the pipe;
(b) the thermal resistance of the thermosyphon or heat pipe;
(c) the thermal resistance of the growing ice annulus.

Under given atmospheric conditions, the overall thermal resistance will increase with ice thickness and thus lead to a diminishing ability to remove heat from the interface. At the same time, the rate of heat supply to the interface—which depends upon both water temperature and the thermal resistance of the water convective system—will not likely decrease. In fact, for a given water temperature, the heat flux density may well tend to increase with the increased velocities often associated with the narrowing gap produced by the growing ice. That is, as the ice grows it does so at a rate which gradually decreases; and at the very point of occlusion the disappearing gap is theoretically capable of producing the rapidly escalating velocities associated with very high heat transfer rates, not to mention viscous dissipation. We appear to face a paradox.

Occlusion is a fact of nature, too complex to be treated within a few pages. This paper merely reports the results of a single investigation. The study is divided into two complementary parts: a theoretical analysis which includes an attempt to model the process of occlusion; and a series of experiments designed to generate data for three different sets of conditions:

(a) single tube conditions, in which the effects of neighbouring solid surfaces are absent: the bulk water flow rate remains unchanged.
(b) twin tube conditions, in which only the proximity effect between a pair of neighbouring tubes is present: the bulk water flow rate remains essentially unchanged.

## NOMENCLATURE

| | |
|---|---|
| $d$ | tube diameter, $2R_0$ |
| $g$ | gap between ice interfaces |
| $h$ | heat transfer coefficient |
| $\mathbf{j}$ | heat flux density |
| $k$ | thermal conductivity |
| $L$ | latent heat of freezing |
| $\mathbf{R}$ | radial displacement of ice interface |
| $Ste$ | Stefan number |
| $T$ | absolute temperature |
| $t$ | time |
| $U$ | water velocity |
| $X$ | penetration into entry region. |

Greek symbols

| | |
|---|---|
| $\alpha$ | angle with flow direction |
| $\Delta$ | difference |
| $\theta$ | temperature measured from the freezing point |
| $\kappa$ | thermal diffusivity |
| $\rho$ | density. |

Subscripts

| | |
|---|---|
| $\pi/2$ | $\alpha = \pi/2$ |
| $m$ | mid-point |
| i | ice–water interface |
| 0 | ice free |
| W | water |
| $\infty$ | free stream. |

(c) occlusion conditions, in which the ice forming between the pair of tubes eventually blocks off the water flow.

## THEORETICAL ANALYSIS

*Interface growth rate*

Consider the two-dimensional system shown in Fig. 1 in which two adjacent pipe surfaces, diameter $d$, and $g_0$ apart, are held at a temperature $\theta_0$ below the freezing point. Let $U_\infty$, $T_\infty$ be the free stream velocity and temperature, respectively, of a cross flow of water. At any point on the ice–water interface, the heat balance equation dictates that

$$\rho L \frac{\mathrm{d}\mathbf{R}}{\mathrm{d}t} = \Delta_{\mathrm{i}} \mathbf{j}$$

where $\mathbf{R}$ is the radial displacement of a point on the interface, and $\Delta$ represents the difference in the conductive heat fluxes $\mathbf{j}$ across the interface at that point. It is evident that $R$ will generally be a function of the angle $\alpha$, measured with respect to the direction of flow. In particular, we are especially interested in the interface equation when $\alpha = \pi/2$: that is, when

$$\rho L \frac{\mathrm{d}R_{\pi/2}}{\mathrm{d}t} = \frac{k_s \theta_0}{R_{\pi/2} \ln\left(\dfrac{R_{\pi/2}}{R_0}\right)} - (j_w)_{\pi/2} \tag{1}$$

in which $j_w$ is the heat flux density in the water, and we have substituted the steady axisymmetric solution for the ice heat flux density. Thus we have assumed that sensible heat in the ice is unimportant (Stefan number $\ll 1$) and the surface is essentially a circular cylinder (as borne out by our experiments).

The water heat flux density depends upon $\alpha$. At $\alpha = \pi/2$, it may be represented as an empirical function of free-stream Reynolds number, the precise form depending upon the proximity of adjacent ice–water interfaces. When the interfaces are far apart each behaves as a single cylinder for which the local heat flux density data are well established [4]. As proximity increases we might expect some departure from these single cylinder relations; and as we approach occlusion, it is clear that an entirely different approach will be necessary.

Given the water heat flux density, equation (1) may be integrated to provide $R = R(t)$ between $R_0$ and $(g_0 + d)/2$. Since the equation can not be written in compact analytic form it is best integrated numerically using a simple forward integration procedure in which the water heat flux density is prescribed afresh for each step.

*A model of occlusion*

It is clear that equation (1) is not difficult to integrate when the water heat flux density is known as a function of ice diameter. It is equally clear that the heat flux density can not be provided entirely from existing data because they do not extend into the occlusion region. Although convective cross flows over parallel pipes have been studied extensively, there appears to be very little information [5] on local heat transfer rates between closely spaced pipes. With this in mind, the treatment of the water heat flux has been divided into three separate regimes.

The first regime corresponds to single cylinder conditions in which the local Nusselt number and heat transfer coefficient at $\alpha = \pi/2$ are already available in the literature [4]. It is merely necessary to write $(j_w)_{\pi/2} = h_{\pi/2}\theta_\infty$, in which $\theta_\infty = T_\infty - T_i$ is fixed and $h_{\pi/2}$ is provided empirically.

The second regime extends the first to include the initial effect of proximity. The above expression for $(j_w)_{\pi/2}$ remains the same but the right-hand side needs closer scrutiny. If this regime is considered to extend to the point where the boundary layers on adjacent interfaces actually begin to interfere with each other, then only before such a point is reached may we continue to treat the flow as a modified version of the first regime: that is, with $\theta_\infty$ remaining unchanged but $h_{\pi/2}$ being altered to reflect velocity modifications in the narrowing interface gap.

If the volumetric flow rate of the water were fixed, the decreasing gap would accelerate the water and thereby increase the local heat transfer rate. However, such a situation is not likely to exist in the field, where an increased resistance to flow would simply decrease the hydraulic gradient upstream (and downstream) of the ice veil. To model such a condition in the laboratory, we simply fix the overall head between two points well upstream and well downstream of the test section. The resistive head developed across the veil thereby automatically reduces the head available to drive the water flow which therefore slowly reduces to zero as occlusion is approached and the veil is gradually forced to withstand the original overall head difference as a hydrostatic pressure difference.

Under these simulated field conditions, the narrowing gap produces two opposing effects on the water heat flux density. Constriction of the flow area tends to increase the velocity (and heat transfer rate), whereas the concomitant increase in fluid flow resistance tends to reduce the velocity (and heat transfer rate). The net result of these two effects may be judged from Fig. 2 which shows the mean water velocity $U_{\pi/2}$ in the gap ($\alpha = \pi/2$) plotted against the gap. It is apparent that the initial effect of the growing ice would be to increase the local heat transfer rate, but only slightly. Once the gap is less than 70% of its original width the effect is reversed, but not until the gap is more than half closed does the velocity (and hence the heat transfer rate) show any substantial departure from its original value. The decrease in heat transfer rate evidently continues throughout this second boundary-layer regime which ends as the boundary layers begin to interact with each other when, finally, we enter the third regime.

Figure 2 also shows the local velocity in the gap for two other situations: a hypothetical constant velocity and the increasing velocity corresponding to a fixed volumetric flow rate.

The third regime is also subject to a velocity field derived from Fig. 2 but is no longer a boundary layer regime. In cold water $Pr \gg 1$, and therefore the momentum boundary layers on adjacent interfaces have merged well before the thermal boundary layers. This fact enables us to describe the convection system in the gap as a hydrodynamically developed, thermal entrance problem whose upstream extremity roughly coincides with the merging of the adjacent thermal boundary layers into a near parabolic temperature profile. It is the decay of this parabola (and the corresponding temperature gradients) which permits the interface to grow more rapidly and thus close the gap.

The point at which the third regime begins, like the location ($\alpha < \pi/2$) at which the thermal entrance problem begins, it not clearly marked (see Fig. 3). In fact we would expect a transitional regime to separate the second and third regimes. None the less, once that point has been chosen, the analysis becomes remarkably simple. As Fig. 3 suggests, we are faced with a two-dimensional thermal entrance problem between two almost parallel surfaces. Using the approximation of parabolic velocity and temperature profiles between parallel, plane surfaces, a simple, integral heat balance reveals that

$$\theta_m(x) = \theta_m(0)\, e^{-KX}$$

where $\theta_m$ is the mid point water temperature, $X$ is the

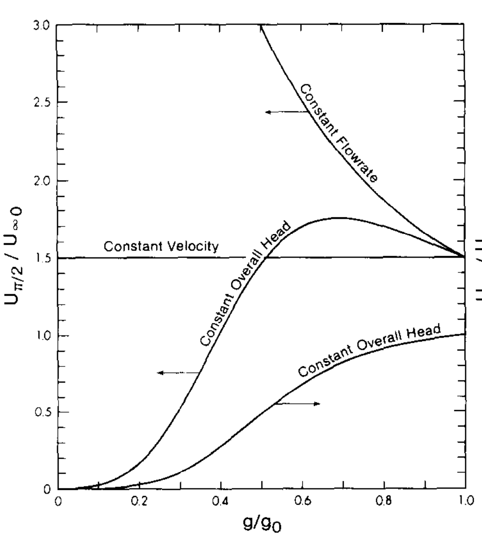


FIG. 2. Water velocity vs gap width.

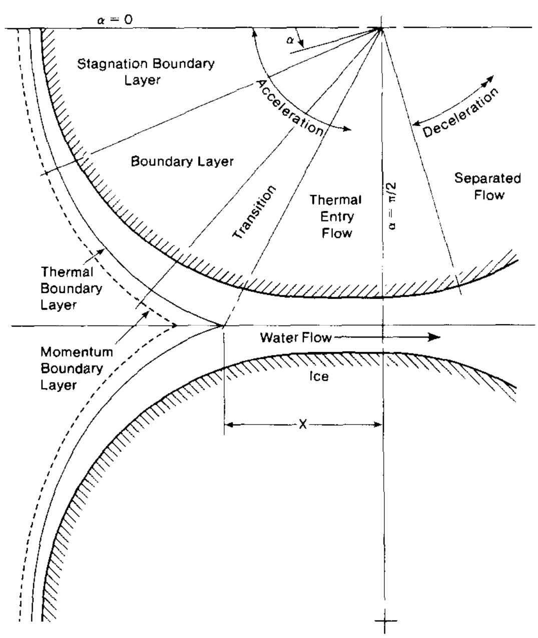


FIG. 3. Flow regimes before occlusion.

distance downstream from the starting point, and $K = 10\kappa/g^2 U_{\pi/2}$. It is clear from this simple approximation that the magnitude of the local water heat flux density, as dictated by $\theta_m(x)$, is strongly affected by the gap. It is also interesting to note that the exponential decay implies a higher interface growth rate downstream of $\alpha = \pi/2$, thus encouraging a latent tendency for the interfaces to form flat parallel surfaces.

## THE EXPERIMENTS

### *Water tunnel facility*

A series of experiments was conducted in the University of Alberta Water Tunnel Facility, housed on two floor levels in the Department of Mechanical Engineering. Tunnel water is discharged from an axial vane pump and driven through an icing unit, or chiller, which lowers the bulk water temperature to a pre-set value, controlled by thermostat. From the icing unit, the water flows up to the higher floor level which houses the test sections, the instrumentation and control panels. The first section after a transitional diffuser contains a series of screens to promote settling and uniformity in the velocity profile. The second section also has a large, rectangular cross section which, because of the correspondingly low water velocities, was admirably suited to the experimental needs of this study. The third section contracts the flow before it enters the higher speed test section, after which it returns to the pump inlet, situated on the lower floor level. Except for the test sections, the tunnel and all its components are lagged with thermal insulation which reduces both the heat gain from surrounding air and the problems associated with condensation.

During the present study, the screens upstream of the low-speed test section were removed, thus relaxing control of free-stream turbulence levels; visual observation did not suggest that turbulence was present but no precise measurements were taken. This arrangement permitted water velocities in the range 0.1–1.0 m s$^{-1}$, with the tests being conducted in the 0.1–0.3 m s$^{-1}$ range. Water temperatures could be set accurately in the range 0.1–15°C: the range used was 0.1–2.0°C.

### *Apparatus and instrumentation*

To produce the ice depicted in Fig. 1, several possibilities were considered: a thermosyphon or heat pipe arrangement; direct circulation of a refrigerant; and the addition of solid carbon dioxide to an alcohol filling. The third cooling mechanism was chosen partly because of its simplicity and partly because it offered lower tube wall temperatures. This last fact promised higher heat transfer (and ice growth) rates, which meant shorter test times, but brought with it unexpectedly high thermal stresses in the ice along with attendant fractures. Fortunately, the thermal stress cracks did not compromise the structural or thermal integrity of the ice, and would not likely appear at all under typical field conditions. Heat transfer rates were not measured directly, but the total amount of heat transferred during the test was confirmed against the estimated amount of carbon dioxide consumed.

Temperatures were measured by means of copper–constantan thermocouples. These were located in the water mainstream, and were also installed along the leading and trailing edges of the tubes at regular intervals. Small though the wires and their epoxy beads were, they were large enough to influence nucleation and crystallization, and therefore gave inaccurate readings during the early stages of ice formation on the tube walls; thereafter they provided accurate measurements. A simple manual switch was used to sweep through the thermocouple readings at regular intervals, and thus enable temperature–time curves to be plotted for individual tube wall thermocouples. From these, an average tube wall temperature–time curve was plotted for each run and then fitted empirically to an exponentially decaying curve in order to simplify the numerical prediction of ice thickness, as discussed later.

A typical set of these data is shown in Fig. 4, from which it is evident that variations in temperature along the tube wall are not very significant, whereas departures from the empirical curve are substantial. Fortunately, this amount of scatter has only a small effect on the rate of ice growth, largely because the ice, once formed as an attenuating layer between the tube and the water, tends to shield the ice–water interface from tube wall temperature variations about the mean exponential curve. Therefore, this treatment of tube wall temperature, despite its errors (which must always be kept in mind), was considered preferable to the more common method of calculating an equivalent step change. The method was found to work well at large times, which are of greatest interest.

Another approximation was to take the ice–water interface as a circular cylinder. Preliminary experiments were found to justify this, and thus greatly simplified the application of theoretical and empirical heat transfer data. With this in mind, the measurements of ice radius vs time were reduced to a single set of measurements: the ice radius at right angles to the

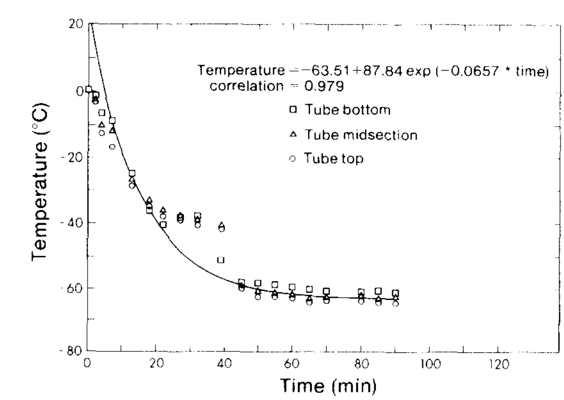


FIG. 4. Tube wall temperature–time curve.

water flow direction. For a single (5-cm-diameter) tube, the ice diameter was measured with external calipers at various locations along the tube, thus generating an average value of radius at the end of each time interval. For the twin tube experiments (5-cm-diameter tubes on 15-cm centres), internal calipers were used to measure the smallest gap between the ice surfaces; when the gap became too small, a feeler gauge was used instead. The long duration of the experiments (1–2 h) enabled a simple stop watch to be used for the measurement of time.

Bulk water velocity was measured by means of a pitot-static tube. At first, this was located upstream of the test apparatus but the low velocities observed contained unacceptable errors. This difficulty was readily overcome by locating the pitot-static tube in the higher velocity test section downstream, and then employing an accurate area ratio for conversion. Water pressure was measured with a simple manometer.

*Test schedule*

After several preliminary runs, the experiments were divided into three series:

*Series A*—dealing with a single tube in an 'infinite' width channel.

*Series B*—dealing with a pair of tubes placed side-by-side in an 'infinite' width channel.

*Series C*—dealing with a pair of tubes placed side-by-side in a channel which the ice would eventually block off completely.

The first series was designed to generate basic data and thus provide both a check on the validity of assumptions and a reference from which to measure subsequent changes. The second series revealed the effect of proximity, and the third shed light on the main subject of the study; namely, occlusion under conditions approximating the damming of a river.

## RESULTS AND DISCUSSION

*Flow visualization*

A photograph taken through the plexiglass bottom of the water tunnel is shown in Fig. 5. Prior to occlusion it was evident that the ice–water interface was well approximated by a circular cylinder, as indicated by the end view shown in Fig. 5 and a frontal view shown in Fig. 6 (of the entire ice block taken outside the tunnel after a completed test). Also noticeable in the upper part of Fig. 5 are the faint trajectories of hydrogen bubbles

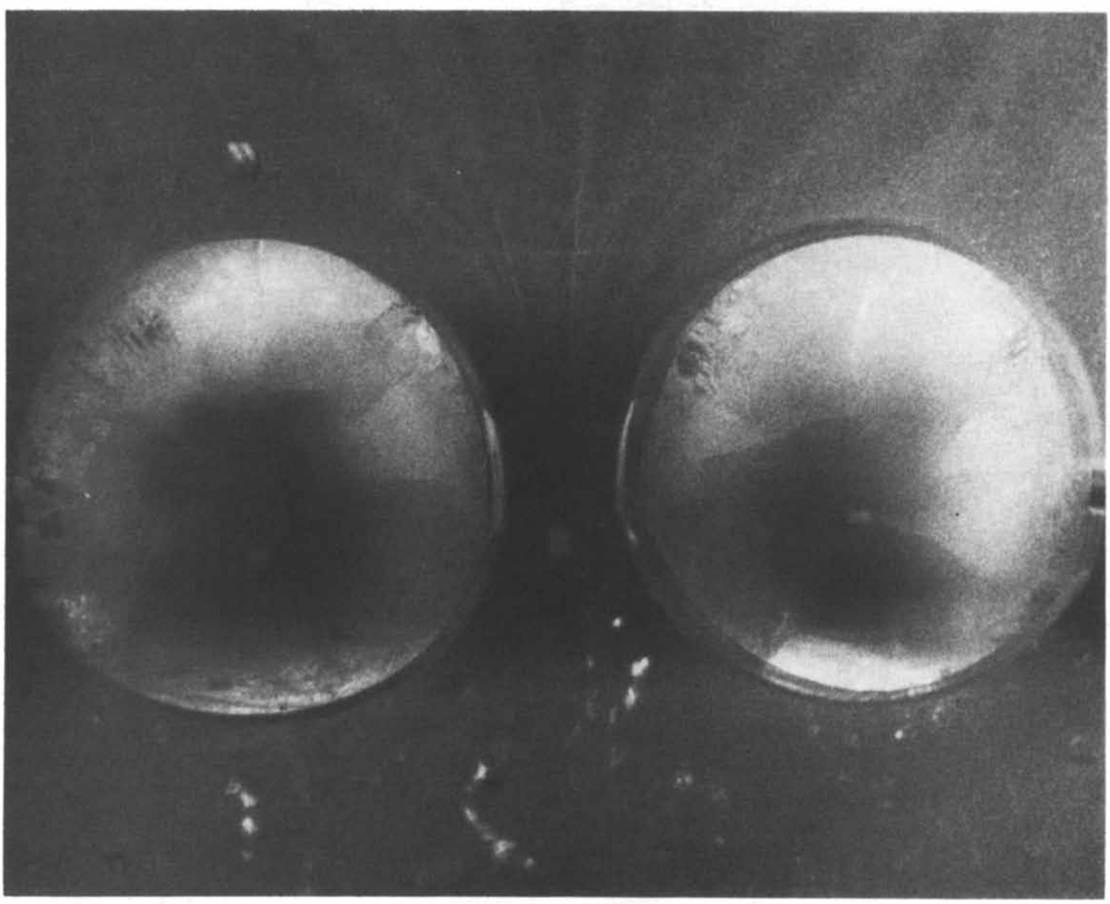

FIG. 5. Early ice shapes: end view.

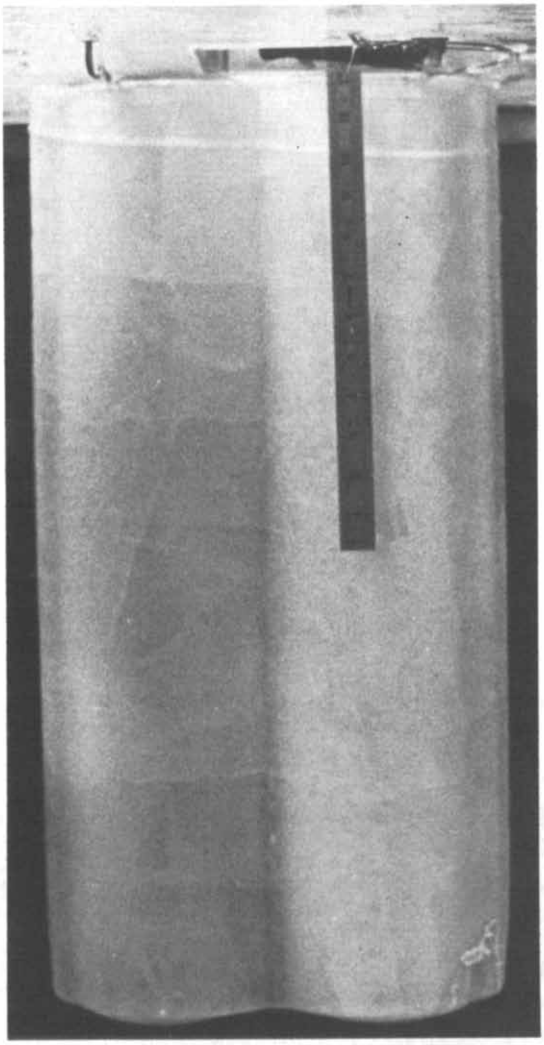

FIG. 6. Final ice shape: front view.

upstream of and between the cylinders: the flow is evidently laminar and quite symmetric.

Figures 7 and 8 show end views some time later. Figure 7 was taken just prior to occlusion, when the mainstream water velocity is reduced and showing signs of incipient stagnation. The photograph clearly reveals the almost parallel, narrow, channel left between the cylinders. Also shown is scalloping of the interfaces immediately downstream of this channel, where the highly adverse pressure gradient has caused a vigorous separated flow. Figure 8 was taken only a short time after occlusion when the water had become stagnant in the vicinity of the merged interfaces. Within a few minutes the cylinders were joined over almost one quarter of their perimeter.

*Single tube data*

Under field conditions, the rate of ice formation will be strongly determined by the velocity and temperature of the water, which together control the convective heat flux at the interface. In order to investigate the effect of this heat flux, two representative water conditions were arbitrarily set: $T_\infty = 0.5°C$ and $U_\infty = 0.3\ m\,s^{-1}$ ('high' flux); and $T_\infty = 0.1°C$ and $U_\infty = 0.1\ m\,s^{-1}$ ('low' flux). These conditions were used for all the ice growth tests, except the initial test which was used to standardize the fitting of the tube wall temperature–time curve.

Figure 4 shows an example of wall temperature–time data together with a fitted exponential curve. As mentioned earlier, the fit does not appear to be particularly good, as a result of some trial and error in the feeding of solid carbon dioxide into the alcohol. However, if this empirical approximation is used to predict the rate of ice growth in slowly moving water ($0.1\ m\,s^{-1}$) at 0.3°C, the prediction (Fig. 9) is found to be fairly accurate, thus establishing confidence in the technique, even when $Ste = 0.38$.

*Twin tube data*

As mentioned previously, these were divided into two runs, one designed to study the effect of proximity and the other designed to study occlusion. In both series

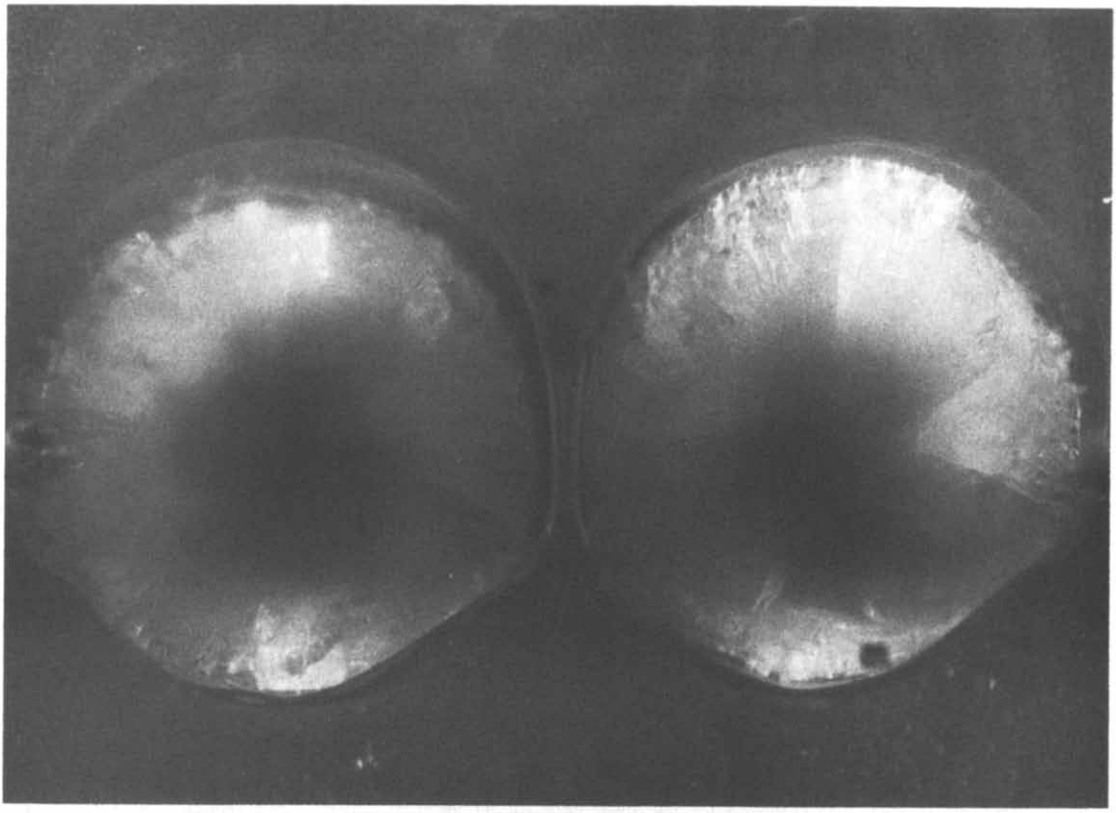

FIG. 7. Occluding ice shapes: end view.

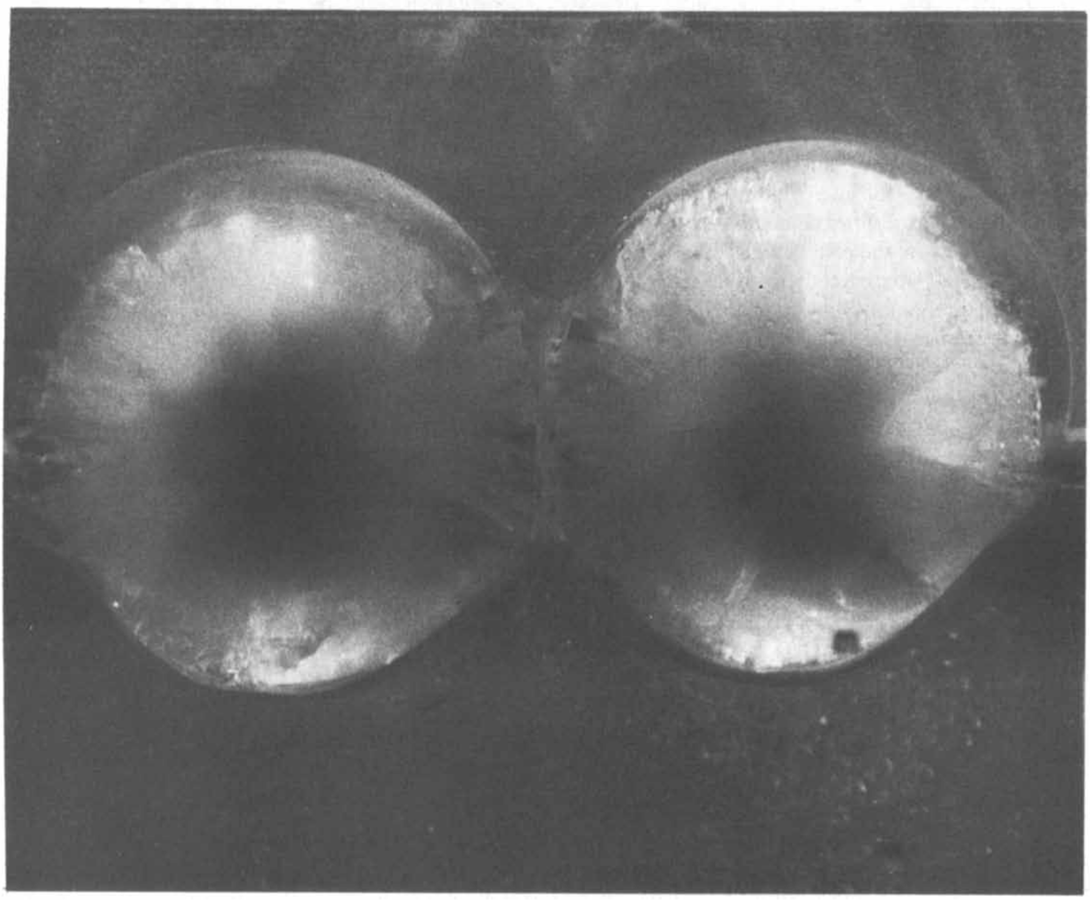

FIG. 8. Final ice shape: end view.

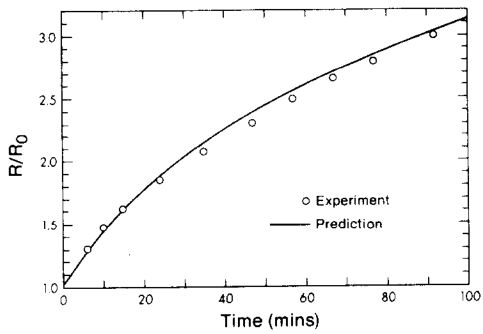


FIG. 9. Single tube ice growth.

the results will be presented as the non-dimensional gap ratio ($g/g_0$) vs time.

Figure 10 shows the effect of proximity. When the convective heat flux is low [Fig. 10(a)], the effect of proximity is seen to be very small, as one would expect for conditions approaching those of a quiescent fluid at its freezing temperature. Only the last few minutes before complete closure reveal an appreciable departure from single tube conditions.

When the convective heat flux is higher, the effect of proximity is more significant, as indicated in Fig. 10(b). The departure from single tube conditions is attributable in part to the tendency of the simplified theory to slightly overpredict ice growth rate, but the principal reason is to be found in proximity. In particular, acceleration through a shrinking gap becomes a significant factor, as discussed in more detail below.

When the two tubes were flanked by lateral plates extending to the walls of the tunnel, conditions closely simulated those for an infinite row of tubes. Corresponding experimental results are shown in Fig. 11. As can be seen, the results differ only slightly from those discussed immediately above. Also shown are theoretical predictions incorporating various occlusion provisions: the lowest curve represents flow conditions governed by a constant overall (tunnel) head; the highest curve represents a constant volumetric flow rate; and the intermediate curve corresponds to a constant velocity (single tube).

At first glance it is tempting to conclude that constant flow rate is the most accurate theoretical model but such a conclusion may be facile. Actual conditions were in fact somewhere between a fixed flow rate and a fixed overall head, and therefore a more thorough discussion of the results is necessary, beginning with the good agreement that is found between theory and experiment for at least 80% of the change in gap width. Such agreement, which is consistent with estimates of experimental error, confirms that the single tube analysis is reliable over a surprisingly wide range of gaps. In the absence of occlusion, these simple predictions may be adequate to the designer's needs.

As we approach occlusion, the problem becomes more complex and it is necessary to list the reasons why the experimental results are most often above the theoretical curves for higher convective fluxes. Perhaps the theoretical model is too simple, especially in assuming a circular cylinder geometry and neglecting sensible heat; or perhaps the empirical heat transfer data are inaccurate. The tube wall temperature–time curve may not be a good enough fit, or the measurements of the closing gap may be too crude. Perhaps free-stream turbulence or viscous dissipation became important.

These possibilities were all tested systematically to reveal, in each case, only a small contribution to an expected departure from the constant overall head prediction. Cumulatively, the explanation might be more plausible were it not for the good agreement observed for all but the smallest gaps. The best explanation appears to be in the effect of gap velocity, as demonstrated by the variations shown in different models. Tunnel conditions were evidently closer to the constant flow rate model than was originally anticipated.

## CONCLUSIONS

This paper has examined the growth of ice around parallel vertical tubes situated in a cross flow. It has shown that glace ice may grow in roughly circular annuli and that this growth will, for certain water temperatures and flow rates, continue until neighbour-

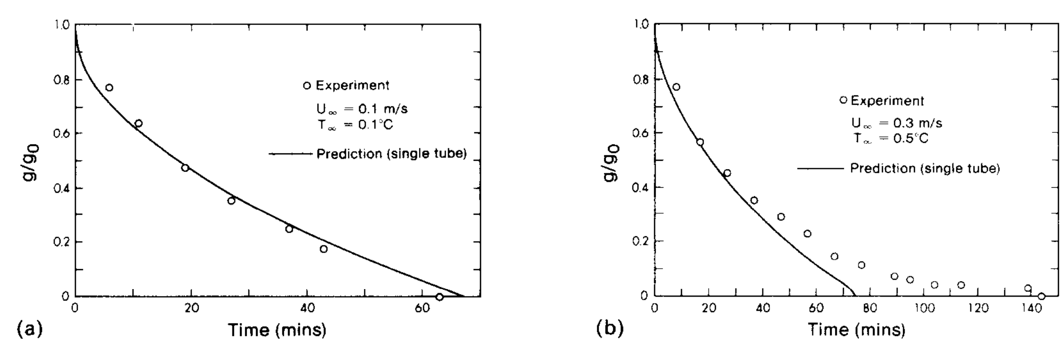


FIG. 10. Gap width vs time: twin tubes. (a) Lower water heat flux; (b) higher water heat flux.

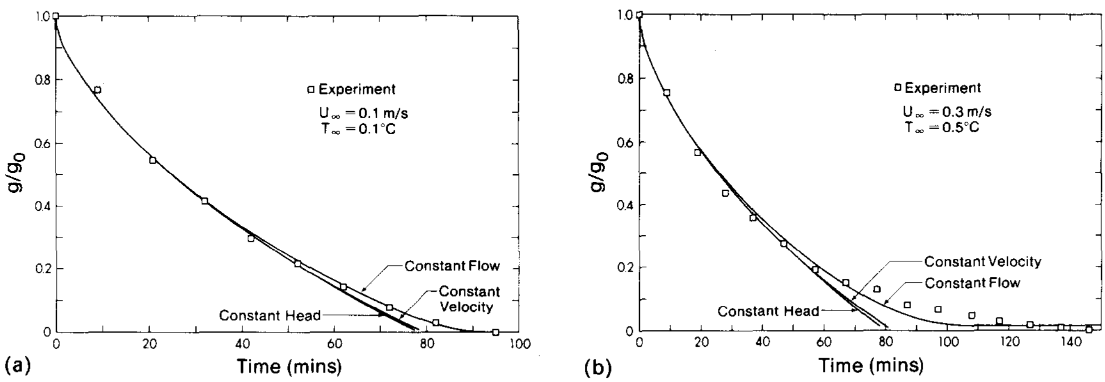


FIG. 11. Gap width vs time: simulated row. (a) Lower water heat flux; (b) higher water heat flux.

ing ice–water interfaces touch and merge to form a solid wall of ice.

Theoretical predictions have shown that ice growth rate is almost identical for a single tube, a pair of tubes and a simulated row of tubes, until the original gap is about 80% filled. That is, for gaps larger than this, the effect of proximity and gap constriction are negligible. For smaller gaps, the theory predicts several possibilities, depending on the control, or lack of control, of the overall water flow rate. It is found that a constant overall head (the condition most closely approximating field conditions) produces the fastest ice growth rate, though not too much different from the rate corresponding to a constant velocity (the condition corresponding to a single tube). The lowest growth rate corresponds to a constant volumetric flow rate, as we would expect.

Experimental results obtained in a water tunnel facility are generally in good agreement with the theoretical predictions. Beginning with a set of single tube data which establish the accuracy of the measurements, the experimental data can be confidently extended into the test series for a pair of tubes and a simulated row of tubes. Consistent with the theoretical predictions, the experiments reveal that single cylinder data would be adequate until roughly 80% of the original gap is filled. For smaller gaps, it is evident that the tunnel was operating quite close to a condition of fixed volumetric flow rate.

A theoretical model of occlusion has been developed consistent with experimental observations. In essence, it is a thermal entry model based on the laminar conditions to be expected in vanishingly small gaps; it also contains the effect of viscous dissipation (which was negligible in the experiments reported here). Although this model is believed to be reliable, the results presented above are not considered to be a good test of it. Clearly this is an area for further work.

*Acknowledgement*—The authors gratefully acknowledge the University of Alberta Central Research Fund Grant which made this work possible.

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## FORMATION DE GLACE SUR DES TUBES SUBMERGES: UNE ETUDE D'OCCLUSION

**Résumé**—On rapporte des calculs théoriques et des mesures expérimentales pour le problème de la formation de glace sur des tubes parallèles et verticaux situés dans un écoulement transversal d'eau froide. Le système a une application au barrage des rivières nordiques. Les résultats suggèrent que le modèle théorique, qui inclut une description d'occlusion, est capable de prévoir la croissance de glace sur le domaine de conditions étudiées en laboratoire.

## EISBILDUNG AN ÜBERFLUTETEN ROHREN: DAS ZUSAMMENWACHSEN DER EISSCHICHTEN

**Zusammenfassung**—Es werden theoretische Betrachtungen und experimentelle Messungen zum Problem der Eisbildung an parallelen vertikalen Rohren vorgestellt, die quer von kaltem Wasser angeströmt werden. Das System findet Anwendung bei der Eindämmung von Flüssen in nördlichen Regionen. Die Ergebnisse zeigen, daß das theoretische Modell, welches eine Beschreibung des Zusammenwachsens der Eisschichten beinhaltet, in der Lage ist, das Eiswachstum für eine Reihe von im Labor getesteten Bedingungen zu berechnen.

## ОБЛЕДЕНЕНИЕ ПОГРУЖЕННЫХ В ЖИДКОСТЬ ТРУБ: ИССЛЕДОВАНИЕ ОККЛЮЗИИ

**Аннотация**—Представлены теоретические расчеты и экспериментальные измерения для задачи льдообразования на параллельных вертикальных трубах, расположенных в поперечном потоке холодной воды. Система применяется при перекрытии северных рек. Результаты показывают, что при помощи теоретической модели, включающей описание окклюзии, можно рассчитать льдообразование в диапазоне условий, проверенных в лаборатории.