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Making Frazil Ice in a Large Ice Tank

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The paper describes a series of laboratory experiments on frazil ice formation in a large body of water, and on subsequent frazil-ice congestion of a water intake located at the bottom of the water body. The experiments sought insights and data regarding flow-field influence on frazil ice formation and ingestion by such an intake. They were conducted using a refrigerated ice-tank at IIHR-Hydroscience and Engineering. The flow field around the bottom intake was monitored using particle image velocimetry. The tank approximately simulated the typical conditions for submerged intakes located in large water bodies. The conditions included wind-induced waves. The experiments are very unusual, insofar that they were conducted at such a large scale. Commensurately, they were not without their challenges; the major ones being to super-cool a large body of water, and to produce frazil ice in a controllable manner in that water. The super-cooled water body in the tank was 21m long x 5m wide x 0.55m deep (58m^3 in volume). After some initial experimental difficulties, it was found that substantial quantities of frazil ice indeed could be formed in a sufficiently controllable and repeatable manner to facilitate experiments on the ingestion of frazil ice by a submerged intake.

1. Introduction

This paper describes a series of laboratory experiments carried out to elucidate frazil-ice ingestion by water intakes. The laboratory experiments are somewhat unique insofar that they involved an effort at controlled formation of frazil ice a large ice-tank in a refrigerated laboratory. They were supported with results from a numerical model of intake flow and ingestion of frazil ice.

Submerged water intakes are used commonly for withdrawing water from rivers and lakes. However, there presently is little known about the interaction of the intake flow field and frazil accumulation by an intake. Additionally, there is little guidance on how to design intakes to minimize frazil ingestion and accumulation. Though numerical models are a useful means for gaining much insight into frazil ingestion by an intake, there remains the need for laboratory experiments aimed at obtaining essential insight. Such experiments inevitably have to be carried out at a fairly large scale, because of the great difficulty (some might say impossibility) of scale-reducing frazil ice for laboratory experiments. Moreover, to be of quantitative use, such experiments must be carried out with reasonable control and repeatability of frazil ice formation.

The writers have attempted such a series of experiments, and achieved modest success. The experiments have not been attempted before (to the best of the writers' knowledge), and indeed considerable uncertainty existed as to their viability because of the difficulty in forming frazil ice in a reasonably controlled manner at such a large scale. The experimental set up, procedure, and early results are presented herein. The experiments themselves focused on the ingestion of frazil ice by a conical intake placed at the bottom of the tank.

2. Ice Tank

Figs 1 and 2 respectively provide a view of the ice tank and give the tank's overall layout and dimensions. The tank is 21m long, 5m wide and 1.5m deep. Water depth in the tank was 0.55m for the experiments. Placed at the center of the tank's floor was a conical intake, which had a 0.30m-diameter rim, and was connected to a 0.14m-diameter outflow pipe. The intake configuration is shown in Fig. 3.

The pipe from the intake was connected to a pump positioned outside the refrigerated lab. Flow, at a rate of 2.24 x $10^{-3}m^3/s$, was drawn through the intake and re-circulated back into the tank through a return manifold that released the flow at the tank's sides by way of two manifold-diffuser pipes. For a scale of 1:10, the equivalent prototype flow rate is $0.71m^3/s$, the flow rate for a small, industrial intake. For all practical purposes, the tank contained a quiescent body of water; currents were neglible, except near the intake. The flow rate was scaled in accordance with Froude-number similitude using a length scale based on intake scale, and amplified in accordance with the size and density of frazil-ice crystals.

The experiments entailed determining the influence of an elevated cap placed above the intake rim support. The idea being that a cap would cause the intake to withdraw water from lower elevations in the water column and thereby reduce the ingestion of frazil ice, whose concentration typically decreases with lower elevation in the water column. The frame consisted of four rods on which the cap could be placed at prescribed heights. The cap was slightly larger than the intake rim for simple building. The results of the experiments with the cap are reported by Chen et al. (2002).

3. Refrigeration System

The refrigeration system was comprised of four air-chillers that dispersed chilled air through a manifold duct system located in the ceiling above the ice-basin. The desired temperature in the ice room was controlled by two thermostats located at the two ends of the room. The air temperature above the ice tank was set at -10 C ± 1°C. The water temperature in the tank usually was at 0°C at the beginning of each series of experiments, and attained a minimum of about -0.02°C during the experiments. Temperatures were recorded using several thermistors and handheld thermometers.

Fig. 1. The ice tank.

The surface heat transfer rate, the rate of heat loss by the water, is an important factor affecting water super-cooling and frazil ice production. The surface heat transfer rate is computed as

$$\varphi = \rho_w c_p y \frac{dT_w}{dt} \quad (1)$$

where φ is heat transfer rate; ρ_w is density of water (1000 kg/m^3); c_p is heat capacity (4.22×10^3 J/(kgC)); y is depth of water (0.55m); dT_w is water temperature change in time t; and dT_w/dt is rate of water temperature (about 2°C per 24-hours when T_w is close to 0°C, and air temperature outside the ice room is 80°C). After replacing these values into Eq.1, φ is 53.6W/m^2. The above equation assumes that the whole water depth is well mixed. This is the case for the frazil ice experiments in small tanks. In the present study, because of the large size of the basin, a mixing water body is difficult to achieve. Therefore, the above estimate is approximate.

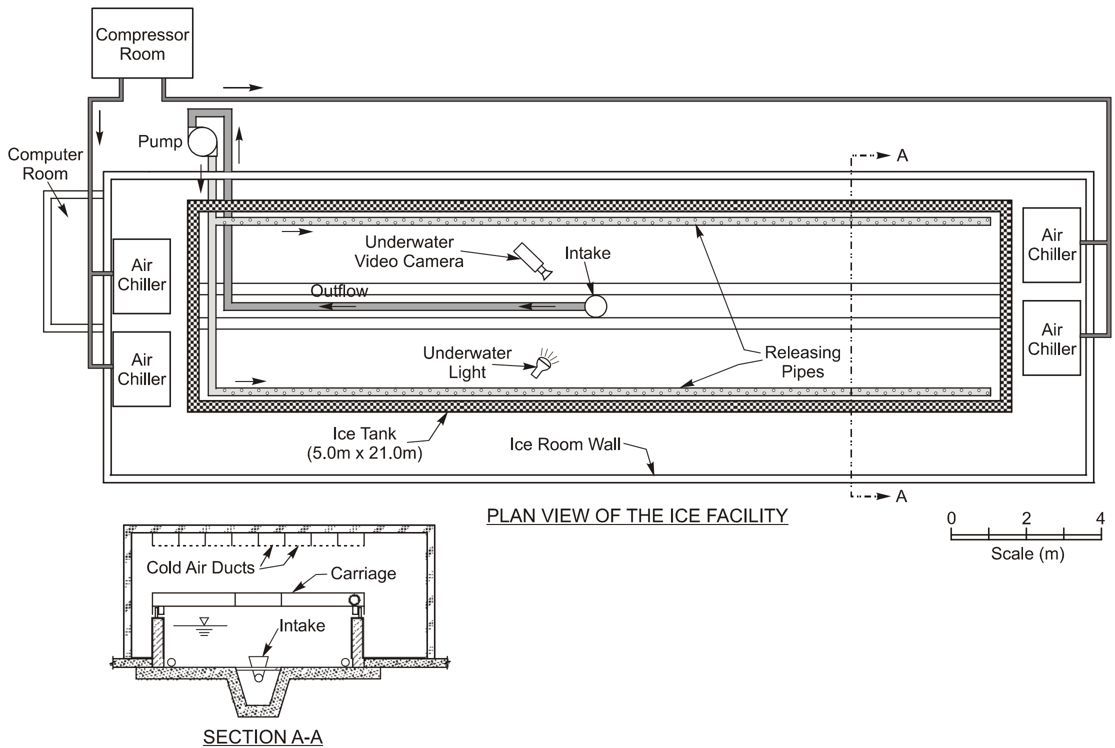

Fig. 2: Layout of ice tank and location of intake.

4. Instrumentation

Air temperature and water temperature in the ice room were measured using platinum resistance thermometers (RTDs). Four RTDs, hung from the ceiling of the ice room about 2.5 m above the basin ground, were aligned along the basin with nearly equal spacing. A RTD, placed at one end of the basin, about 0.1 m above the basin bottom (water depth was about 0.55 m), measured the water temperature. Each RTD was calibrated with a precision of 0.05°C. Temperature data from the array of the four RTD's and the water RTD were automatically logged at six-hour intervals using a computer.

The temperatures measured by the four RTDs were close; the largest temperature difference was less than 0.05° C. The water temperature variation over the basin was small, less than 0.02° C. The underwater camera, placed at the bottom of the basin, about 2 m away from the intake, enabled direct observation of the frazil ice accumulation on the intake. An underwater video camera, placed in the tank, about 2m away from the intake, was used for observing frazil-ice formation and collection on the mesh placed over the intake's mouth. To help visualize frazil ice at the intake, an underwater light, sitting on the basin bottom, about 2 m away from the intake, and about 1 m away from the underwater camera, was used to illuminate the area around the intake (see Fig. 1).

The dimensions of frazil ice crystals collected on the mesh placed over the rim of the intake were measured by means of a crystalography magnification lens marked with graduated scales.

5. Procedure

In natural water bodies that are quiescent, frazil ice forms in consequence to water super-cooling by frigid air usually accompanied by wind. The winds agitate the water surface, and cause the water to super-cool instead of forming a surface layer of skim ice. For the present experiments, four fans (see Fig. 1) were placed along the basin walls and one further fan was placed on the carriage, blowing toward the intake area. The agitated water surface (Fig. 4) approximately replicated the water surface of a windswept body of water.

Fig. 4. Surface waves (about 25mm in height) created by fans.

Before commencing an experiment, the ice skimmer (see Fig. 1) mounted on the tank's carriage was used to skim the ice cover from water surface and shove it to the two ends of the basin, where it was retained. The water surface around the intake was left open.

Two approximate levels of water agitation were used to cause the water to super-cool when exposed to frigid air, and to mix the super-cooled water over the water depth. Fans placed along the tank's walls produced one level of agitation, herein termed surface agitation. The fans produced small, irregular waves (about 25mm in height) that agitated the water surface and prevented an ice cover from reforming and insulating the water. All the while, the intake discharge was maintained.

The greater level of agitation was produced manually using two large paddles to stir the water over its full depth, thereby augmenting the surface agitation created by the fans. The crudeness of the agitation did not facilitate precise characterization of the levels of turbulence and mixing created by the two levels of agitation, other than indicating the agitation levels to be surface or full depth. However, it did enable the effects of water agitation on the amount of frazil-ice formation to be examined. It is well known that increased agitation of water increases super-cooling, and thus the amount of frazil ice produced (Ettema et al., 1984). For the experiments, using rakes to mix the water around the intake increased water agitation.

Once the initial few frazil crystals were spotted in the water, a frazil-ice-collection grid was placed over the mouth of the intake so as to measure the rate of frazil-ice ingestion by the intake. The grid, not unlike a form of scale-reduced trash rack grating, comprised a wire mesh of steel wire forming 1mm-square openings. The mesh collected all frazil drawn to the intake's mouth.

The volumetric concentration of frazil ice in the water drawn subsequently to the intake, and the total number of frazil-ice particles drawn to the intake were estimated using the mass of frazil ice collected on a mesh. Series of experiments were conducted to measure frazil-ice collected on the intake after 5, 10, 15 and 30 minutes of flow withdrawal by the intake. The experiments were repeated with the intake fitted with a cap of variable height above the intake rim.

The volumetric concentration of frazil ice formed in the water column was estimated by dividing the volume of the frazil ice, collected on the mesh over the intake, by the volume of the total flow into the intake, for a period when the intake was not blocked by the collected ice; i.e.,

$$C_v = \frac{Vol_{ice}}{Vol_{water+ice}} = \frac{M_{ice}/\rho_{ice}}{QT} \qquad (2)$$

where C_v is volumetric concentration; Vol_{ice} is the volume of the collected frazil ice; $Vol_{ice+water}$ is the total volume of the frazil ice and water entered the intake; M_{ice} is the mass of the frazil ice collected on the mesh in the period T; T is the time of the period; ρ_{ice} is the density of frazil ice, 920 kg/m^3; and Q is the discharge of the intake ($2.24\times10^{-3}\text{m}^3/\text{s}$).

Frazil ice concentration, $C_{n,}$ in terms of number of particles was estimated as

$$\begin{aligned} C_n &= \frac{C_v}{\text{Volume of average frazil ice particle}} \\ &= \frac{C_v}{(\frac{1}{4}\times2\times10^{-3})^2\times\pi\times(0.1\times10^3)} \\ &= 6.37\times10^8\times C_v \end{aligned} \qquad (3)$$

The typical frazil ice particle formed in the basin was a discoid, 2 mm in diameter, 0.1 mm thick. This size is about the same as observed during experiments in prior studies (Ettema et al., 1984; Daly, 1984, 1994; Ye, 2002).

6. Intake Flow Field

The flow velocity measurements obtained by means of PIV (using dye as tracer), together with flow streamlines obtained by means of dye, concur with the flow fields obtained by means of numerical simulation. The numerical simulation of the flow field is shown in Fig. 5, in which the data points refer to successive positions of dye heads drawn to the intake. Because the flow field outside the intake is symmetrical about the vertical centerline of the intake, only those pathlines to the left of the intake center are shown. The pathlines indicate that water is fully drawn from around the intake, including the regions above and to the sides of the intake. Flow streamlines determined using the numerical model show that flow is drawn directly downwards and towards the intake center.

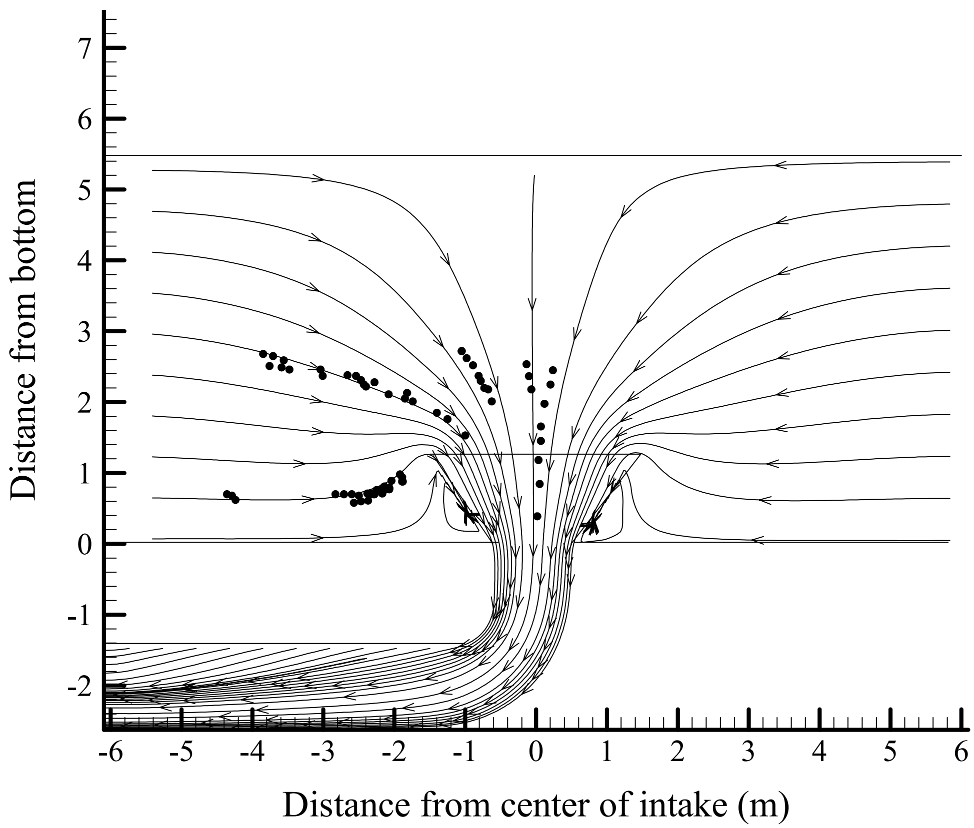

Fig. 5. Flow streamlines (numerical model) and pathlines (data from PIV measurement of dye heads) at intake.

7. Frazil-Ice Concentration and Accumulation

As mentioned above, frazil ice drawn to the intake was collected by means of a mesh placed over the intake's mouth. Fig. 5 shows frazil ice accumulating on the intake rim. The mass of the frazil ice collected was measured for several time stages during each experiment. Frazil ice accumulation at the center of the mesh was greater than at the rim of the mesh and there the intake. This finding reflects that more frazil ice particles are drawn to the center of the intake, as would be expected from the flow field shown in Fig. 5.

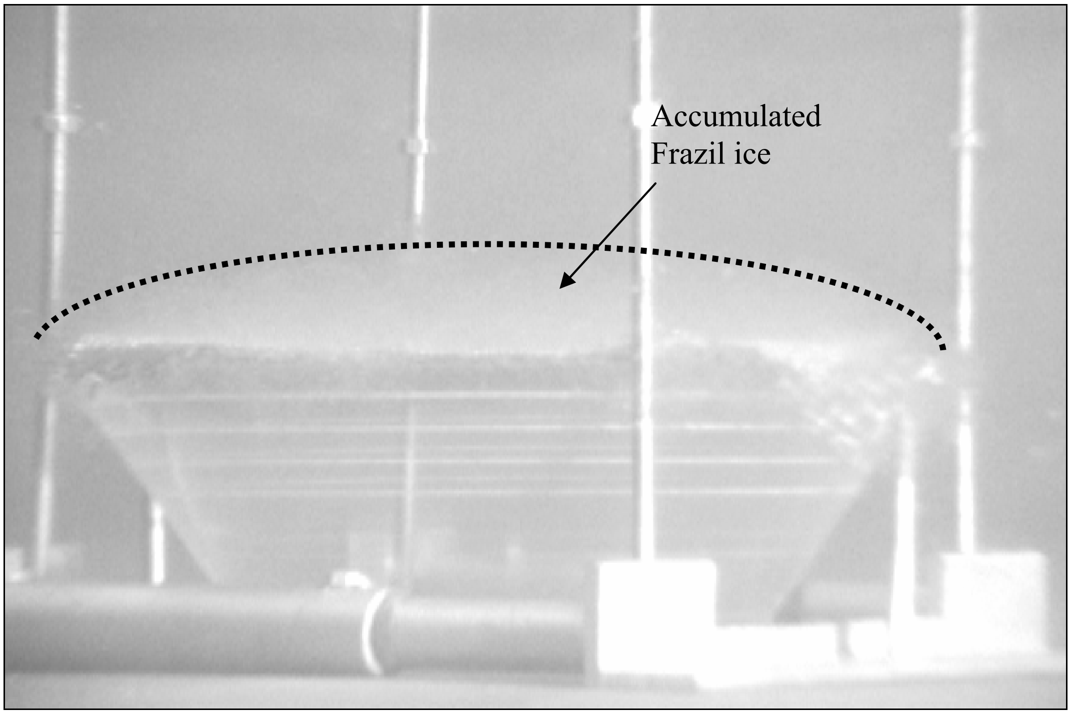

Fig. 5. Frazil ice accumulated on mesh over intake rim. The vertical posts were used to support a cap placed at variable elevation above the intake rim.

As evident in Fig. 6, the frazil ice crystals or particles accumulated were of uniform diameter and thickness. Crystal diameter averaged 2mm and thickness 0.1mm.

The temporal relationship between mass of collected frazil ice and elapsed time, (5, 10, 15, and 30 minutes), is shown in Fig. 7. During the initial stage, from time ‘o’ to point ‘a’ on the curve, the amount of frazil ice collected increased slowly with time. Then, the collected frazil ice increased rapidly (between ‘a’ and ‘b’). When the amount of frazil ice collected on the mesh began to choke the flow into the intake (point ‘d’), flow into the intake decreased. Consequently, less frazil ice is drawn to the intake, and the mass of frazil ice collected on the intake asymptotically approach a maximum value. Point ‘d’ is taken here to represent the maximum mass of the collected frazil ice. The overall relationship between the frazil ice entrained into the intake and the time forms an asymptotic, S-shaped curve.

Fig. 6. Uniform-sized frazil ice crystals on collection mesh.

The relationship shown in Fig. 7 is similar to the relationship between frazil ice concentration and the time lapsed after seeding (Ettema et al., 1984). The initial stage of the relationship between frazil ice and time corresponds to the initial stage of frazil ice concentration and the time after seeding. At this stage, frazil ice production just starts, and a large amount of frazil ice production remains to be produced. The shapes of the two relationships at the rapid production stage are similar. During this stage, a large number of frazil ice particles are produced. Therefore, the collected frazil ice increases rapidly. This happens some time after the seeding. At the last stage, both relationships asymptotically approach the maximum. But the reasons responsible for the asymptotic form of both relationships are different. For the relationship between frazil ice concentration and the time after seeding, the major reason is the secondary nucleation of frazil ice maintaining at a constant rate; for the relationship between the frazil ice entrainment and time, the main reason is that the intake is severely blocked, so a small amount of frazil ice is entrained into the intake. If the intake were not blocked by frazil ice, the discharge of the intake would be constant. Consequently, the relationship between frazil ice entrainment and the time should be a straight line. Note that the lengths of the time for each stage may not necessarily be the same for the two relationships.

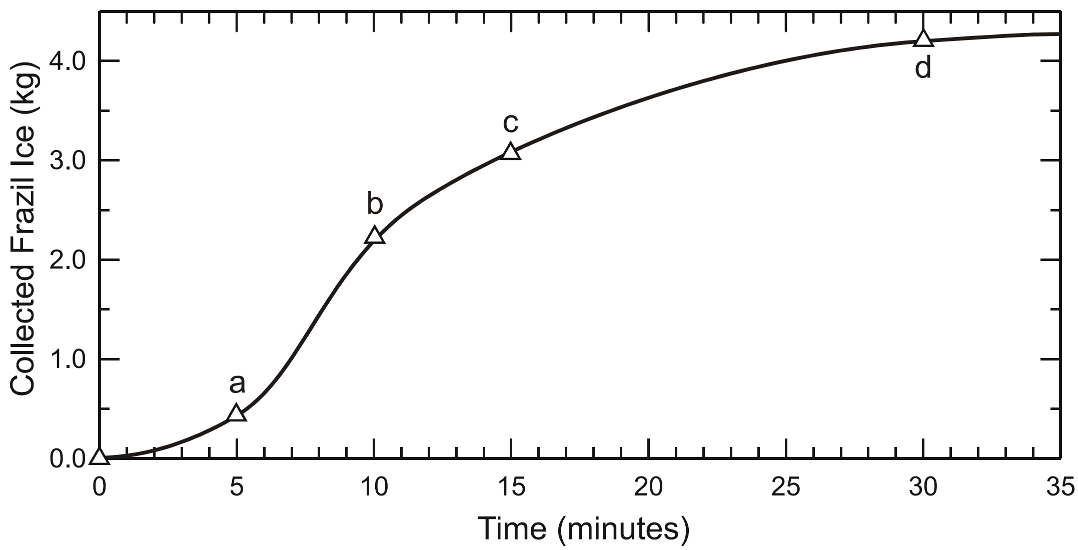

Fig. 7. Temporal rate of frazil ice accumulation on mesh.

8. Frazil Ice Concentration

The frazil ice concentrations at points (a) – (d) in Fig. 7 were estimated using Eqs 2 and 3. The results are listed in Table 1.

Table 1. Temporal variation of frazil ice concentration on collector mesh over intake in ice tank (surface agitation of water).

Stage of Collection (Fig. 14)		*a*	*b*	*c*	*d*
frazil ice concentration	volumetric	6.58×10^{-4}	3.22×10^{-3}	4.43×10^{-3}	6.0910^{-3}
	particle number	4.19×10^{5}	2.04×10^{6}	2.82×10^{6}	3.88×10^{6}

The concentrations in Table 1 are comparable to those estimated in prior studies: e.g., 10^{-4} to 10^{-2} (volumetric concentration, Ettema et al., 1984; Ye, 2002); 1.80 x $10^5/m^3$ to 9.82 x $10^5/m^3$ (number concentration, Daly and Colbeck, 1986), 1×10^4 to $1\times10^6/m^3$ (number concentration, Schaefer, 1950; Osterkamp and Gosink, 1982). For points (b), (c) and (d), the number concentrations are larger than those in other experiments. This outcome may result from the assumption used in Eq. 3; i.e., all frazil ice particles have the same discoid size.

Table 2 compares frazil ingestion rates for the surface agitation (waves) and full-depth agitation (paddle-stirred) of the ice-tank waters, and compares also the rates determined from the numerical simulation. The data are shown for the intake without and with cap at two elevations, *H*, above the intake rim, whose diameter is *D*. The frazil ice concentrations obtained with only surface agitation of the water in the ice tank are smaller by about an order of magnitude than those with full-depth agitation. Table 2 indicates that the frazil-ice concentrations determined from the numerical model (Chen et al., 2002) and the ice tank, with full-depth agitation, are in reasonable agreement, given the approximation natures of the ice-tank experiment and the numerical simulation. The difference in frazil number concentration between surface agitation and depth agitation indicates the sensitivity of intake ingestion of frazil ice to two factors:

1. The concentration of frazil ice formed, which in turn depends on the extent to which water is super-cooled; and
2. The distribution of frazil ice over the water depth. Agitation caused frazil ice to be somewhat more uniformly over the water depth, and thereby would have resulted in greater overall amount of frazil ice drawn to the intake.

Table 2. Comparison of frazil-ice concentrations.

H/D		0.30	0.70	1.43 (no cap)
numerical model		0.33	0.60	1.16
ice tank	full-depth agitation	0.42	0.78	1.08
	surface agitation	0.037	0.19	0.42
		frazil concentration: 10^6 particles/m^3 of flow		

9. Collapse of Mesh

When the intake was allowed to continue withdrawing water for a period beyond that in Fig. 7, frazil ice continued to collect on the intake mesh until pump suction forced the inward collapse the mesh and frazil into the intake cone, and completely plugging the intake. Fig. 8 shows the collapsed mesh and frazil molded to the shape of the intake cone.

Fig. 8. Frazil ice blockage of mesh eventually caused mesh and ice to collapse into intake cone.

10. Repeatability

A question that necessarily arose with the experiments concerned their repeatability. Tests with intake fitted with a cap showed that indeed the amount and ingestion rate of frazil ice were repeatable. Several tests were run to ascertain the extent to which cap elevation reduced frazil-ice ingestion. The results, presented in Fig. 8, show that repeatable performance was obtained.

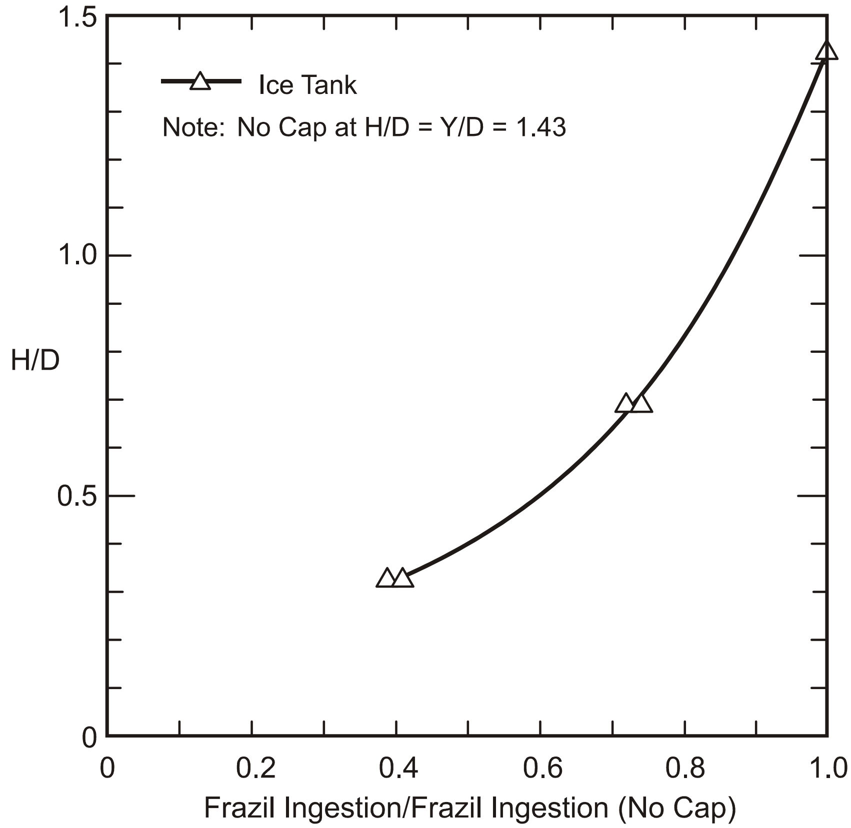

Fig. 9. Influence of intake-cap height/rim diameter (H/D) on quantity of frazil ice ingested by intake. The experiment results are taken from Table 2 for full-depth agitation.

11. Concluding Comments

The ice-tank experiments are among the first laboratory attempts at forming frazil ice on a large scale ($58m^3$) under laboratory conditions. Prior experiments (e.g., Ettema et al., 1984; Ye, 2002; Doering and Morris, 2003) involved small (about $0.1m^3$) volumes of water and studied fundamental aspects of frazil ice formation. The present experiments, involving about $58m^3$ of water, proved to be reasonably successful, showing that frazil ice can be formed in a fairly controllable and repeatable manner in a large tank. They indicate the possibility for further laboratory studies on the interaction of frazil formation and accumulation in flow fields prescribed by local conditions, such as those produced by submerged water intakes.

Further work is needed to develop the ice tank so as to enable better control and instrumentation of frazil ice experiments. Also, there is scope for work to improve the procedures followed in preparing frazil ice in a large ice tank.

12. References

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