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NRC FRAZIL ICE RESEARCH FACILITY

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Abstract: Frazil ice is a type of ice that forms in fast-flowing super-cooled water, consisting of small ice crystals suspended throughout the water column, which is notorious for adhering to all submerged objects it comes in contact with. Frazil is infamous for blocking water intakes in rivers and estuaries as ice crystals stick and build up on the intakes' trash racks, eventually leading to degraded operation and/or shutdown. This paper describes the development and operation of a new frazil ice research facility at the National Research Council of Canada where frazil ice can be reliably generated and its interaction with objects studied under controlled repeatable conditions. The new facility features a relatively large water volume of 120 m^3 and turbulent flow speeds up to 1.1 m/s. The methods developed to initiate frazil growth and monitor the presence of frazil and its concentration are described. Results from a set of initial experiments on frazil ice are presented and discussed.

1 INTRODUCTION

Frazil ice is a type of ice that forms in fast-flowing super-cooled water, and which consists of small ice crystals in suspension in the water column. Because the crystals are in an unstable environment, they tend to adhere to all submerged objects. Frazil ice is notorious for blocking water intakes in winter, as ice crystals adhere and build up on the trash racks. Such blockages negatively impact water supply facilities, hydropower plants, nuclear power facilities, and vessels navigating in cold waters, and can lead to dramatic impacts, such as a town being left with insufficient water reserves for fire protection, a nuclear facility not getting the cold water required for cooling, or a vessel being forced to shut down its engines and drift.

Our theoretical knowledge of frazil ice is currently quite limited, in part because field and laboratory data on frazil ice is difficult to obtain and hence relatively scarce. New experimental research and field data is needed to gain an improved understanding of frazil growth and its interaction with structures, and to develop and validate effective strategies for mitigating negative impacts caused by frazil. Hopefully, such new understanding will eventually lead to theoretical and numerical models that can reliably predict frazil growth and its behaviour. Experimental research on frazil should be carried out at a sufficiently large scale to minimize impacts arising from the impossibility of scaling frazil ice crystals produced in the lab. Further, as turbulence (the turbulent energy dissipation rate) is one of the main drivers in the growth of frazil crystals, it is also important to be able to create conditions that are sufficiently turbulent to be representative of conditions in natural rivers.

Frazil was generated in a 21 m (L) x 5 m (W) x 0.55 m (water depth) tank (58 m^3 water volume) at the University of Iowa (Ettema *et al.*, 2003; Chen *et al.*, 2004), with the objective being to test the blockage of a small water intake (which had an inflow speed of approximately 0.15 m/s) by frazil. The tank's bottom was flat and no thrusters were used to generate currents – therefore the current was solely produced by the pump at the intake, was minimal, and constrained to the vicinity of the intake (the rest of the water body was essentially still). Fans were used to produce wind in order to agitate the water surface and cause some turbulence. The air temperature was set at -10 °C, and super-cooling levels never exceeded 0.02 °C. Four frazil samples were taken during the experiments to produce estimates of the amounts of ice that collected on the intake's mesh. These estimates cannot be interpreted as suspended concentration estimates as they reflect the total amounts of ice accumulated on the mesh over time. When calculated using the intake's discharge values, the volumetric concentrations were averaging 0.12% over a 30-minute period.

A similar experiment was conducted by the University of Bergen at the Hamburg Ship Model Basin (HSVA) (Smedsrud, 2001). Frazil ice was generated in a 20 m (L) x 6 m (W) x 1 m (water depth) tank (120 m^3 water volume) in order to test frazil ice entrainment of sediment in salt water (36-38‰). The tank's bottom was also flat, but thrusters were used to generate currents within the tank. Maximum flow speeds were reported to be on the order of 0.3 m/s. Fans were used to produce moderate wind speeds (~20 km/h). The air temperature was maintained between -14 and -18°C. Volumetric concentrations estimates of frazil ice were produced using a few frazil samples taken with a 5 L water bottle, and using the changes in the measured salinity values over time (as crystals form, salt is expelled and the salinity of the surrounding water body increases); these concentration estimates ranged from 0.02 to 0.13% (per volume).

The goals of the present work were to reproduce the flow conditions in a natural river and learn how to create, manage and measure frazil ice on a large scale in an existing 18 m by 7 m by 1 m deep ice tank. In this paper the steps taken to modify the facility for this purpose will be described, as will the procedures developed to grow and conduct experiments with frazil ice in the new facility. Results from an initial set of experiments in which 20 distinct frazil events were generated and monitored are also presented and discussed in this paper. These experiments were the first of their kind to be conducted at the National Research Council of Canada (NRC), and similar experiments where frazil ice is generated in a large-scale basin have previously been carried out only a handful of times in the world. While several small-scale laboratory studies have previously been reported in the literature (in small tanks of ~1 m^3, e.g. Clark and Doering, 2006), the authors are aware of only two previous studies in which frazil ice was generated in larger tanks (> ~2 m^3, e.g. Ettema *et al*., 2003; Smedsrud, 2001).

2 NRC FRAZIL RESEARCH FACILITY

2.1 Ice Tank

An existing ice tank facility located in Ottawa, Canada, consisting of a 21 m long by 7 m wide by 1 m deep rectangular basin (18 m long by 7 m wide useable area excluding the melt pit) located within a cold room that can be chilled to -20°C was modified to enable frazil ice generation. The ice tank can be filled with water or drained as a required and is fitted with a water-tight access gate. It is also equipped with a motorized main tow carriage and a light service carriage that both move along rails mounted atop the two longer tank walls. The ice tank was originally developed in the early 1980s and since then has been used primarily for applied research involving scaled simulation of floating ice sheets, ridges and ice floes.

2.2 Current Generation System

The ice tank was modified to enable generation of a relatively fast and turbulent current, similar to conditions in rivers where frazil is known to grow in nature. Two 15 m long by 1.2 m tall masonry block walls were constructed, partitioning the tank into a 3.5 m wide central test channel and two narrower side channels, as shown in Figure 1. Four variable-speed 1.9kW electric thrusters were installed, two in each of the side channels. When operating, the thrusters forced the water in the side channels to flow in one direction, forcing a return flow down the central test channel in the opposite direction. A set of curved walls and flow guides was designed and installed at both ends of the tank to encourage the flowing water to turn 180° with minimal losses, thereby maximizing velocities in the center test channel (Figure 2). Four straight guide walls were installed at the upstream end of the central channel to help straighten the flow entering the test section. With 0.95 m water depth, the current generation system was able to generate turbulent flows in the 3.5 m wide central test channel with mean speeds up to 1.1 m/s.

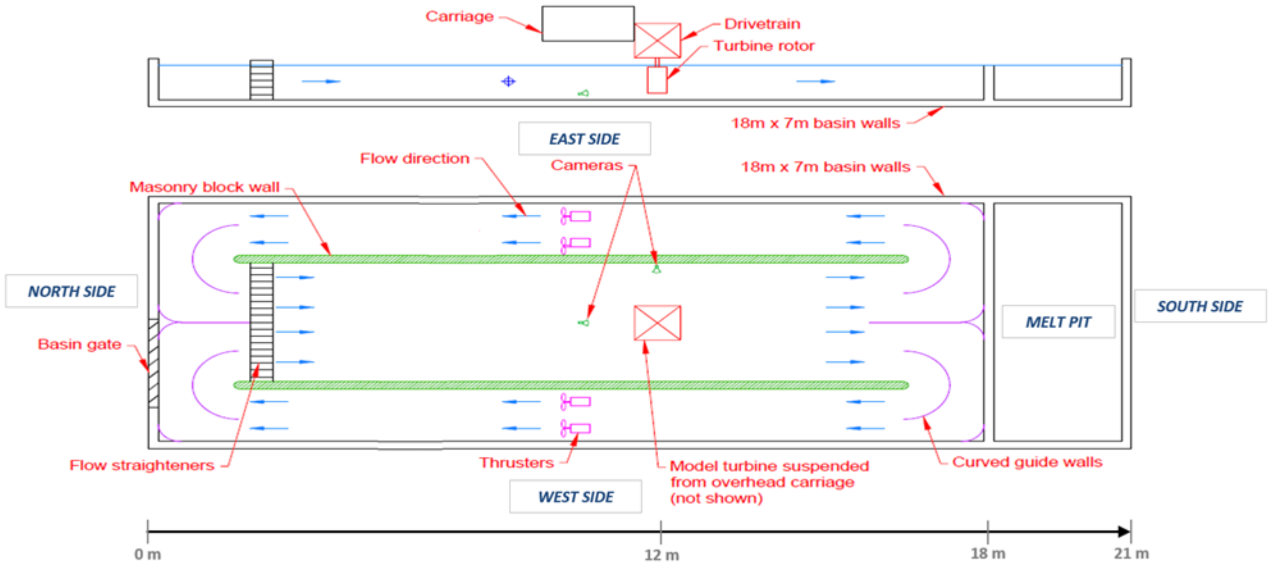
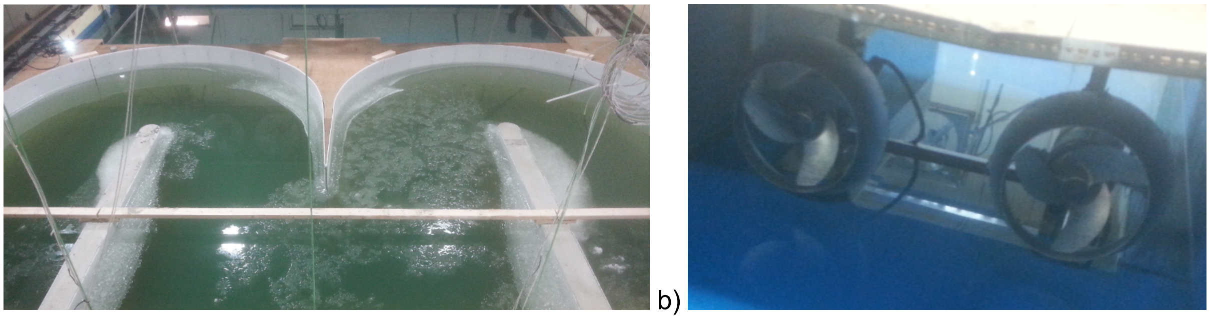


Figure 1*:* Sketch of the current generation system in the 21 m by 7 m ice tank.



a) b)

Figure 2*:* Current generation system equipment: a) partition walls and curved guide walls, b) thrusters.

2.3 Wind Generation System

A bank of five fans was located above the melt pit at the south end of the tank and operated to generate a strong local wind blowing upstream above the water surface within the central test channel. At maximum setting, local wind speeds at the test site were around ~75 km/h, depending on proximity to the fans. The wind action on the water surface generated small waves and spray composed of fine droplets of water. This wind action is thought to be largely responsible for the initial seeding (fine droplets freezing in the cold air and then falling back into the water body) and subsequent initiation of frazil ice formation at the beginning of each event.

2.4 Instrumentation

Two types of temperature sensors were used throughout the experiments: RTDs (platinum resistance temperature detectors) and Optical Gauge Sensors (OGS). RTDs were calibrated with a precision of 0.015°C. The optical sensors use optical fiber and measure strain induced from temperature changes with a high precision (less than 0.01°C). Sensors were installed to measure water temperature at three depths (0.15, 0.45, and 0.70 m below the water surface) at three locations within the tank: a) in the central test channel upstream and downstream from the test section, and b) downstream of the thrusters in the eastern side channel. Similarly, air temperature sensors were installed near the ceiling close to the refrigeration unit and above the center of the basin, as well as close to the water surface downstream of the test section. Both types of sensors (RTDs and OGS) were installed at each measurement location. While the OGS system shows considerable promise, it is a new system and, as expected for new systems, did not always function properly. Despite these difficulties, some of the OGS data was of good quality and useful.

Two acoustic sonars (a 1.5 MHz upward-looking sonar, and a 3.0 MHz side-looking sonar (Figure 3) were used to characterize the flow and detect frazil ice within the water. The upward looking sonar was mounted on the floor of the tank, in the center of the test channel, 3 m upstream of the test site. The side-looking sonar was mounted 1 m downstream of the test site, on the eastern partition wall. A 10 MHz ADV (Acoustic Doppler Velocimeter), sampling at a frequency of 25 Hz, was used to measure velocity at the center of the central channel just upstream of the test site. Outputs from these velocity sensors were used to monitor flow velocities and detect the presence of frazil ice.

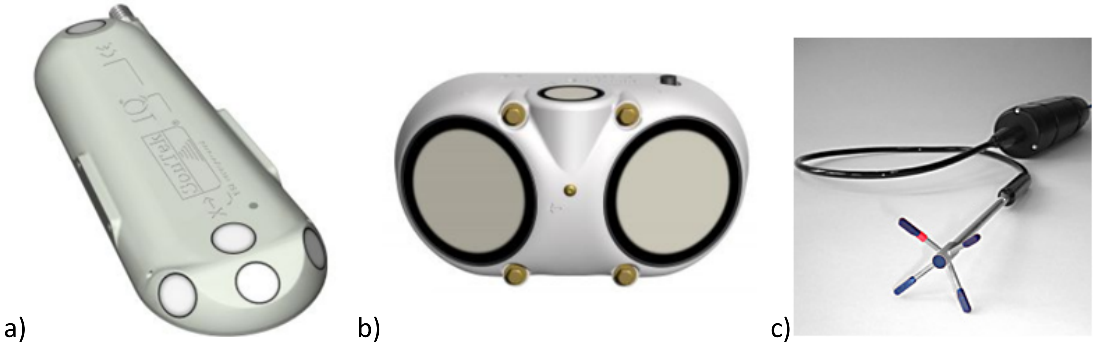


Figure 3*:* Velocity sensors: a) 1.5 MHz upward-looking sonar, b) 3 MHz side-looking sonar; c) 10 MHz 3-axis ADV.

A bespoke frazil sampling frame was developed and used to efficiently and rapidly collect samples of the frazil crystals that passing through the test site. The ice crystals were collected on a 0.6 x 0.4 m rectangular piece of wire mesh (#18 with 1 x 1 mm openings) that could be submerged at the test site, held in place for period of time, and then retrieved (see Figure 4). An electronic scale (precision of 0.001 kg) was used to weigh the mass of ice crystals collected on the wire mesh.

Finally, two underwater cameras were installed in fixed locations in the tank close to the test location, while a third underwater camera attached to a long stick was used to collect movies in other, difficult to access, locations not covered by the other cameras.

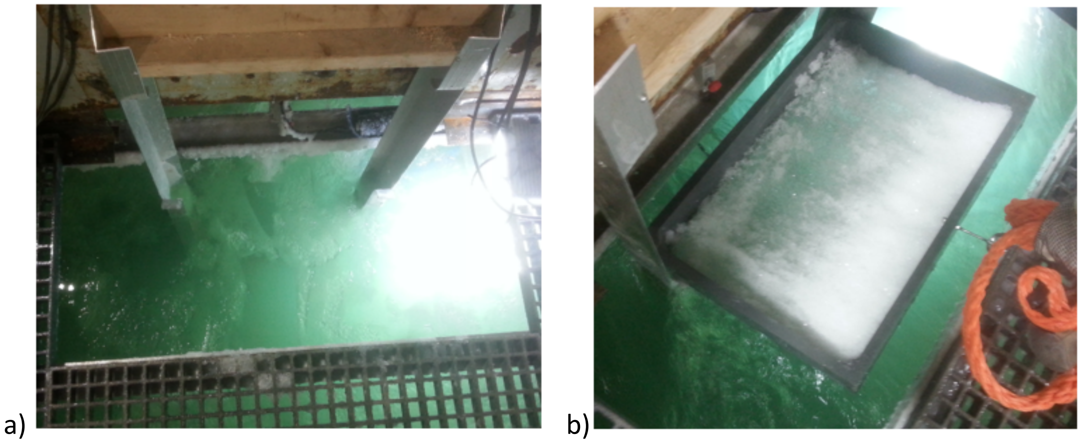


Figure 4*:* Apparatus for sampling frazil: a) sampling frame submerged; b) rectangular wire mesh with ice crystals.

3 FRAZIL GENERATION AND DETECTION

3.1 Frazil Generation

A procedure was developed whereby frazil ice could be reliably generated, studied and then dissolved/melted in an optimized manner, so that tests could be conducted at a rate of up to two frazil events per 8-hour day. This required very tight control over water temperature, heating and cooling.

The process was started with the water temperature around at 0.5 °C or slightly lower. With the air temperature set to -20 °C, the currents at 1 m/s, and the wind speeds at 75 km/h, it would take anywhere between 2-4 hours for the water to cool to its freezing point. When the water temperature reached 0 °C, super-cooling would be imminent. Wind action on the water surface is thought to be an important factor in initiating frazil ice formation in the tank. It is believed that small ice crystals formed in the air (formed from fine water droplets that froze in contact with the cold air) would cause the initial seeding of frazil crystals as they fell into the water body and were entrained within the flow. No other external seeding was required to initiate the generation of frazil ice. From there, frazil production increased rapidly and large amounts of crystals were produced over a short period of time. It is believed that frazil nucleation occurs through the process of secondary nucleation (Daly, 1984; 1994; 2008), through which ice crystals are formed from parent crystals shedding off small ice pieces from their irregular surfaces (which either detach resulting from shear forces, or resulting from a collision with other crystals or another object). Maximum super-cooling (minimum water temperature) generally occurred 15-30 minutes after the onset of super-cooling. After a further 15-30 minutes, the water temperature would rise back to 0 °C, signaling the end of the active phase and of ice crystal growth.

Experiments could then be stopped or continued into the passive phase. Once the decision to stop was made, the air temperature was set to +20 °C, all doors of the basin were opened (to allow warm air in), and all fans were shut down. Relatively warm water from the melt pit (maintained at a temperature of a few degrees over the freezing point) was then pumped into the main water body. The currents were usually kept at 1 m/s to allow for homogeneous mixing and efficient convective transport of this warm water in all areas of the tank. The air temperature would rise very quickly to above-freezing values. The water temperature would typically stay around 0 °C until all ice was melted, after which point it would begin warming above 0 °C. The water temperature was monitored very closely to ensure it did not rise above 0.5 °C. Once this degree of warming was achieved, the hose pumping water from the melt pit was removed and another test could be started. The entire “reset” cycle normally took roughly 4 hours.

3.2 Frazil Detection

Three methods were used to detect and quantify frazil ice: (1) monitoring outputs from the three acoustic sensors, (2) monitoring water temperature readings (super-cooling levels suggest frazil formation), and (3) physically sampling the frazil ice crystals.

The intensity of the acoustic backscatter from an underwater sonar or ADV depends (in a very non-linear way) on the number of ice crystals, their size distribution, and their shape. While accurately quantifying the concentration of suspended ice from acoustic measurements is challenging, one can use acoustic signals to detect the presence of frazil with a high degree of confidence due to the marked change in the character of the acoustic signal. The signals from the acoustic sensors (either the SNR, or the raw amplitude counts) would start to rise as the frazil crystals began to form, reflecting the presence of particles suspended in the water column. The acoustic signals generally reached a peak value when maximum super-cooling levels (minimum water temperatures) were reached, reflecting the presence of a large volume of suspended ice crystals. The acoustic signal amplitudes were found to be a reliable indicator of the presence of frazil ice; however, the influence of frazil agglomeration or floc size on the acoustic signal was not explored in this brief initial study.

Frazil sampling was performed by submerging a rectangular piece of wire mesh into the upper half of the water column at the test site. A lot more ice was found to be present in the upper part of the water column (as expected), especially as each event progressed and the crystals grew in size and agglomerated such that their buoyancy was large enough to overcome the downward entrainment from turbulent eddies. The adopted procedure was to collect one sample every 2 to 3 minutes throughout the period of active frazil growth. The first crystals generated during each event were visually imperceptible, and it was sometimes difficult to judge when sampling should be started. In a few experiments, sampling was continued well into the passive phase (up to almost 240 min after the onset of super-cooling).

The duration for which the mesh was kept submerged in the water had to be adjusted as an event progressed, depending on the concentration of ice crystals. If submerged for too short a duration, the amount of ice collected would be so small that its mass could not be reliably measured. If submerged too long, the mesh would become fully clogged, forcing the flow to pass around it, so that the volume of ice collected on the mesh would grossly underestimate the "real" frazil ice concentration. Sampling durations typically ranged from 60 seconds at the beginning of an event, down to just a few seconds towards the end of an event when the ice concentration was at its peak.

Over 150 good quality samples of frazil ice were collected during the initial set of experiments. For each sample, a volumetric concentration (C_i) estimate was calculated using the following:

$$[1]\ C_i = \frac{V_i}{V_w + V_i} = \frac{M_i/\rho_i}{(UA\Delta t)+(M_i/\rho_i)}$$

where V_i and V_w are respectively the volumes of ice and water flowing through or collected on the mesh, M_i is the mass of ice collected on the mesh (measured from the sample), U is the flow speed through the mesh during the sampling process (calculated from time-averaging the ADV measurements), A is the mesh area perpendicular to the flow ($A = 0.23625$ m^2), Δt is the sampling duration (typically between 5 and 60 seconds), and ρ_i is the ice density (920 kg/m^3).

4 TYPICAL EXPERIMENTAL RESULTS

4.1 Velocity Profile

To date tests have been conducted with flow speeds of 0.5 and 1.0 m/s. Vertical profiles of the flow velocity at the test site were acquired using the upward-looking sonar during each test. The sonar measured the averaged flow velocities within a series of 10 cm vertical layers, and further averaged over a period of 10 seconds. Figure 5 shows typical vertical profiles of flow speed for both the 0.5 m/s (red) and 1.0 m/s cases (black). It can be observed that the vertical profiles are fairly uniform, with fast flows persisting 15 cm above the tank bottom. The measured velocity profiles remained fairly stable over time, even during the active phase of rapid frazil growth. The near-surface velocities (without frazil) were verified through independent measurements obtained using a 3-axis ADV.

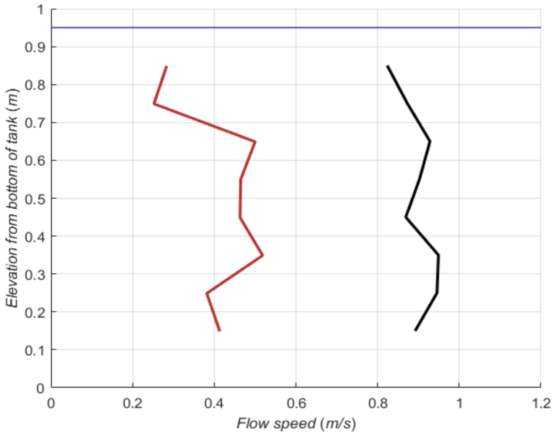


Figure 5: Typical vertical velocity profiles for 0.5 m/s flows (red) and 1.0 m/s flows (black).

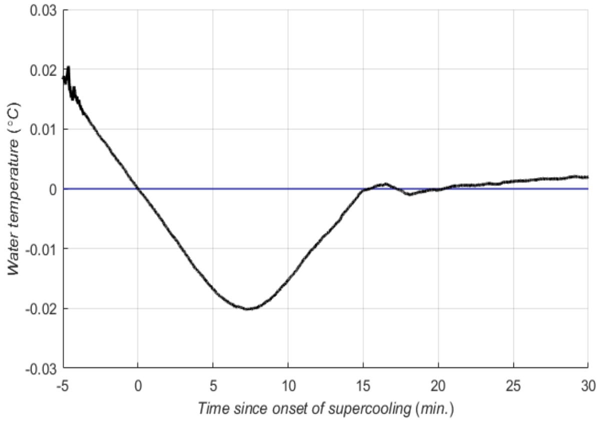


Figure 6: Water temperature measured during a typical frazil event showing super-cooling to -0.02°C.

4.2 Water Temperature

Water temperature data was collected from all RTDs and OGS sensors throughout each test. Overall, all temperature sensors gave similar readings regardless of their location within the tank, except for the ones located directly downstream of the thrusters (which generated small amounts of heat). This was expected because of the high flow speeds and the relatively strong level of turbulence, which produced a well-mixed environment throughout.

A typical super-cooling curve is presented in Figure 6. The water temperature curve followed a similar pattern during virtually all experiments, although the total duration and maximum super-cooling levels varied from one experiment to the next. During the initial phase, as heat is being lost from the water body to the air, the water temperature decreases towards 0°C. The water then continues to cool and becomes super-cooled, at which point frazil crystals start to form. As the crystals grow, they release latent heat which is transferred to the water body, counter-acting the heat loss from water to air. Maximum super-cooling levels (minimum water temperatures) are attained when the heat generated through ice crystal growth equals that lost to the air. For the case shown in Figure 6 this happens roughly 7 minutes after the onset of super-cooling. From here on, ice crystals still continue to grow and multiply through secondary nucleation, further increasing the rate of heat generation, which eventually overwhelms the heat loss from water to air. During this period, the water temperature rises back towards 0°C. Once the water temperature reaches 0°C, all crystal growth stops. It should be noted that no surface ice forms during the event due to the strong turbulence.

The lowest water temperature value measured by an RTD sensor in this initial set of experiments was -0.026 °C. While this may appear to be small, it is actually very close to the -0.02 °C value reported by Ettema *et al*. (2003) where experiments were conducted in a similar laboratory facility. Similar values were also reported in rivers (minimum of -0.06 °C and average of -0.03 °C in Richard and Morse (2008) and Morse and Richard (2009); minimum of -0.025 °C in Richard et al., 2011).

Figure 7a shows box plots of the minimum water temperature recorded in 20 distinct frazil events as a function of flow speed. On these plots, the colored boxes represent the 25th, 50th (red line) and 75th quartiles, whereas the gray lines extending outside of the boxes show the data outside of this range. The green and blue colors are used to denote experiments conducted at flow speeds of 0.5 and 1.0 m/s, respectively. Figure 7a suggests that the minimum temperature is insensitive to flow speed, although the data seems to be more variable at lower speeds. It is also interesting to note that the values reported above in Ettema *et al*. (2003), Richard and Morse (2008), Morse and Richard (2009), and Richard *et al*. (2011) cover a wide range of flow speeds ranging from near-zero to upwards of 2 m/s in the St. Lawrence River, yet the super-cooling levels all appear to be very similar.

The results plotted in Figure 7b suggest that the duration of the super-cooling events as insensitive to flow speed. Typically, super-cooling events in the laboratory lasted between 20-30 minutes, and none of the events lasted more than 30 minutes. In contrast, some events in rivers have been reported to last much longer (e.g., up to a few hours in Richard and Morse (2008) and Morse and Richard (2009)).

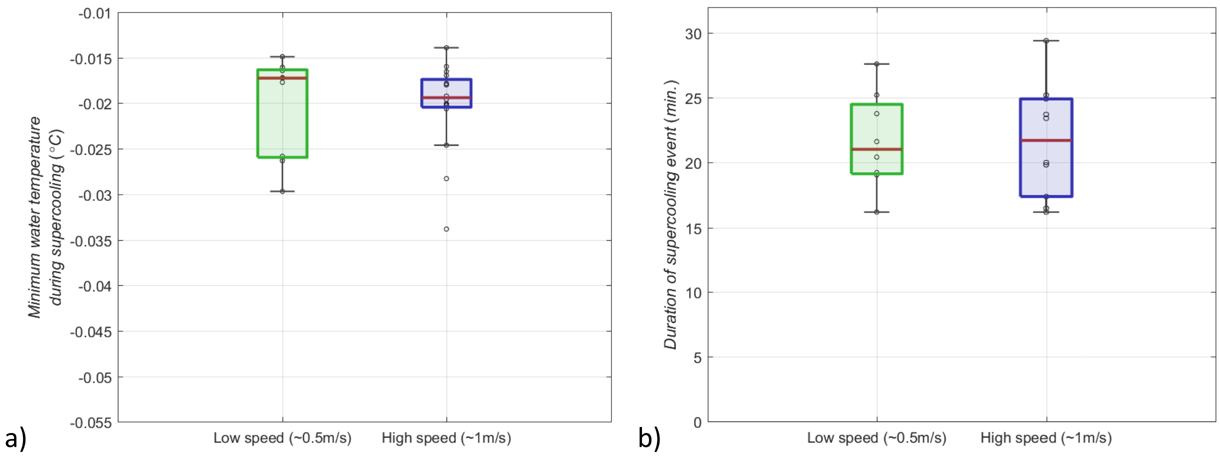


Figure 7*:* a) Minimum water temperature as a function of flow speed; b) Duration of super-cooling events as a function of flow speed.

4.3 Frazil Detection and Quantification

Overall, 159 frazil ice samples were obtained and analysed over the initial phase of experiments discussed herein. For each sample, pictures of the ice crystals accumulated on the mesh were taken. While those were not analyzed quantitatively it was found that by the end of each super-cooling event, all crystals appear to be roughly similar in size (suggesting a fairly uniform distribution), discoid in shape, and the vast majority had a diameter of approximately 1 mm. This was consistent from test to test, and representative of all experiments conducted. The crystal size observed in these experiments is similar in range to the values reported by others (2 mm in Ettema *et al.* (2003), and Chen *et al*. (2004), 0.4 mm in Richard (2011)).

Figure 8 shows the estimated volumetric frazil concentrations as a function of time for 20 distinct frazil events. Blue dots represent experiments conducted at 1 m/s, while green dots represent those at 0.5 m/s. Maximum concentrations appear to plateau in the 0.03 to 0.08% range. These values are not unlike the few other values reported in the literature: 0.12% in Ettema *et al.* (2003) and Chen *et al*. (2004); and 0.02 to 0.13% in Smedsrud (2001). The estimated relative uncertainty on these concentration values is approximately 20%.

Using the maximum frazil concentration estimates discussed above, an estimated dominant ice crystal diameter of 1 mm (as observed in the samples), a diameter-to-thickness ratio of 8 (Daly and Colbeck, 1986), and assuming the size distribution is uniform, it is estimated that the total number of frazil ice crystals per unit volume is on the order of 3-6 million crystals/m^3. This compares favorably to estimates reported in the St. Lawrence River, which were in the range of 3-15 million crystals/m^3 (Morse and Richard 2009; Richard *et al*. ,2011; Richard *et al*., 2015).

Although fewer data points were collected in the passive phase for the tests conducted at lower flow speeds, the data suggest that less ice is created at flow speeds of 0.5 m/s when compared to the amounts produced in higher flow speeds of 1 m/s. At higher speeds, the ice concentration curves in the super-cooling phase rise more sharply than their counterparts at lower speeds. This makes sense as higher flow speeds generate more turbulence, which drives the growth of ice crystals. Figure 9a shows the maximum concentration values measured during the active (super-cooling) phase of each event, while Figure 9b shows maximum concentration values over the entire event, including the passive phase. It was also visually apparent during the experiments that significantly more ice was produced at higher flow speeds.

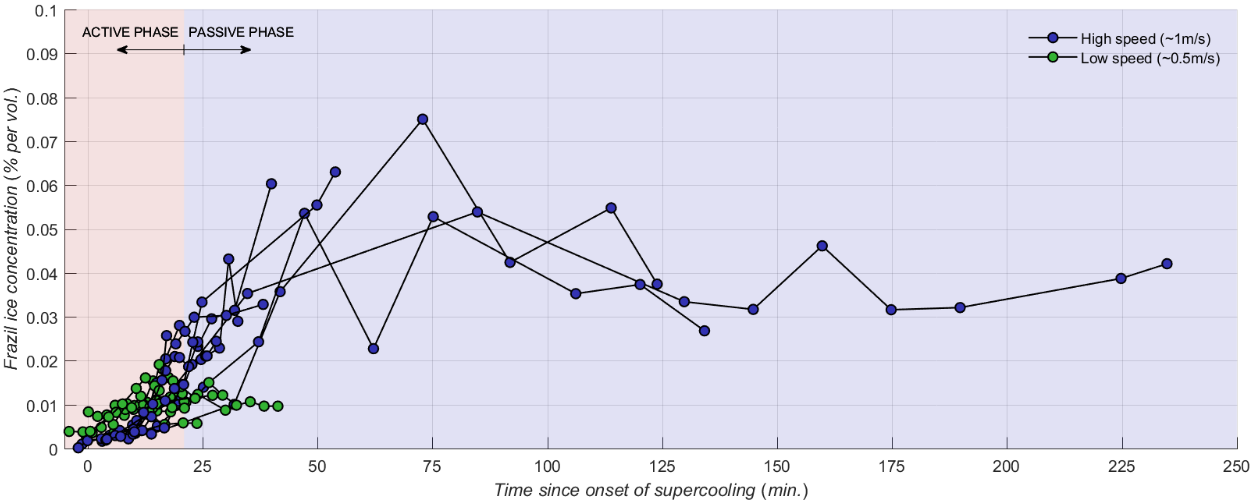


Figure 8*:* Volumetric frazil concentration estimates over time from the onset of super-cooling (the duration of the active period corresponds to the mean of all events).

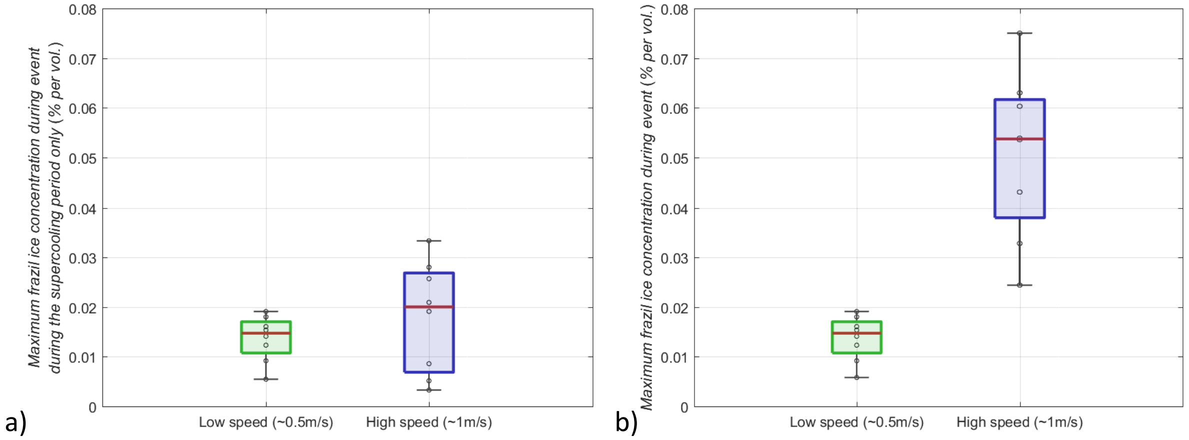


Figure 9*:* Maximum frazil ice concentration as a function of flow speed: a) super-cooling period only; b) entire event (active and passive phases combined).

5 CONCLUSIONS

An existing test facility at the NRC labs in Ottawa has been modified to enable controlled generation of frazil ice in conditions similar to those in natural rivers. The new facility features a relatively large water volume of 120 m^3, turbulent flow with mean speeds up to 1.1 m/s, wind speeds up to 75 km/h, and air temperatures down to -20°C. A test procedure was developed and refined to enable successive frazil events to be generated within ~5 hours of each other. Frazil ice crystals were found to grow spontaneously once the necessary conditions were established; no artificial seeding was required. A set of experiments has been conducted in which 20 distinct frazil events were generated and monitored. Two direct methods (visual observation and sampling) and two indirect methods (water temperature and acoustic backscatter intensity) were used to detect the presence of frazil. Estimates of frazil concentration were developed from analysis of the ice mass collected on a metal screen submerged into the flow. Sonar backscatter was found to be a reliable indicator of the presence of frazil; however, further research is required before reliable estimates of frazil concentration can be inferred from such instruments.

The collected data shows that minimum water temperatures achieved during the experiments were similar in range to values reported in the literature for both field and laboratory conditions, and that those values are similar for flow speeds of 0.5 and 1.0 m/s. The duration of the super-cooling events ranged from 15-30 minutes, which is similar to what has been reported in other laboratory experiments, but is much shorter than other events observed in the St. Lawrence River. Maximum values of volumetric frazil concentration in the range of 0.03 to 0.08% were estimated (with a relative uncertainty of ±20%), which compares favorably to other values reported in the literature (both laboratory and field). Assuming a dominant diameter of 1 mm for each crystal (estimated visually from the samples and the mesh size), approximately 3-6 million crystals/m^3 were present within the water body during a typical frazil event (which, again, compares favorably to other values reported in the literature).

The new frazil ice research facility discussed in this paper can now be used to study the growth and behaviour of frazil and its interaction with submerged objects such as water intakes and hydrokinetic turbines under controlled laboratory conditions.

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