Laboratory measurements of frazil ice properties in saline water

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Frazil ice forms in freshwater bodies such as rivers and lakes as well as in salt-water bodies such as oceans and estuaries. Several laboratory studies have been performed to examine the size and shape of frazil ice crystals in saline water. Some studies observed growth of disc-shaped crystals similar to freshwater frazil crystals (e.g. Kempema et al. 1993; Martin and Kauffman 1981), whereas other studies have observed dendritic ice crystal growth (e.g. Hanley and Tsang 1984; Smedsrud and Henrik 2001).

This study builds on previous research by producing and photographing frazil ice crystals and flocs in a laboratory setting using freshwater and water at salinities of 15 ‰ and 35 ‰. The experiments were performed in the University of Alberta’s Civil Engineering Cold Room in a frazil ice production tank. The tank was equipped with four propellers used to control the turbulence intensity in the tank. High resolution digital images of the ice crystals were captured using a digital camera through two square glass cross-polarizing filters located flush to the glass wall of the tank. Water and air temperatures were measured and recorded throughout the experiments. Water temperature measurements were used to compute the extent of supercooling. A MATLAB image-processing algorithm was modified to analyze the digital images to determine properties of the frazil ice crystals such as particle sizes and shape. In saline water a combination of disc, hexagonal and dendritic shaped frazil ice particles were observed along with smaller flocs. In freshwater frazil ice particles were predominantly disc-shaped and larger flocs tended to form. The average size of individual frazil ice particles in saline experiments was 0.55 mm and in freshwater experiments was 0.61 mm. As salinity increased, the total number of frazil ice particles detected also increased.
1. Introduction and Literature Review

There have been a limited number of studies investigating the shape, size, growth and flocculation of frazil ice in saline water in a laboratory or natural setting. In freshwater studies, the frazil particles have been predominantly reported as disc-shaped (Gosink and Osterkamp 1983, Daly and Colbeck 1986, Ye et al. 2004, Clark and Doering 2006, 2008, Ghobrial et al. 2012, Mcfarlane et al. 2015). In saline water, some studies have reported that frazil ice grows in disc shapes, similar to freshwater (Martin and Kauffman 1981, Kempema et al. 1993, Ushio and Wakatsuchi 1993) and other studies have reported that frazil ice grows dendritically (Hanley and Tsang 1984, Ushio and Wakatsuchi 1993, Smedsrud Henrik 2001).

For freshwater, several studies have reported measurements of the size and shape of frazil ice particles. Disc-shaped particles with diameters ranging from 23 μm to 5 mm and lognormal size distributions have been reported in a number of studies (Gosink and Osterkamp 1983, Daly and Colbeck 1986, Ye et al. 2004, Clark and Doering 2006, 2008, Ghobrial et al. 2012, Mcfarlane et al. 2015). Kempema et al. (1993) performed laboratory experiments and reported disc diameters of 1 to 5 mm and 1 to 3 mm in fresh and saline water (29.14 ‰ to 32.00 ‰), respectively. Martin and Kauffman (1981) performed laboratory experiments and reported disc-shaped particles measuring approximately 1 mm in diameter at a salinity of 35.5 ‰. Smedsrud and Henrik (2001) performed laboratory experiments and reported an average diameter of 2 mm for irregular shaped frazil ice crystals in water of salinity between 36 ‰ and 38 ‰. Ushio and Wakatsuchi (1993) observed dendritic crystals with diameters of 2 to 3 mm for simulated windy, high-salinity conditions in the laboratory. They also observed disc-shaped crystals with a diameter of about 5 mm for lower salinity and simulated calm air conditions. They suggested that the crystal shape and mechanism of growth are dependent on the degree of supercooling, where larger amounts of supercooling are more likely to produce dendritic growth. Summarizing, the reported sizes of frazil ice particles in saline water are comparable to freshwater observations, and the particles have been observed to be both disc-shaped and dendritic. Note that there have been no previous measurements of the size distribution of frazil ice particles in saline water.

There is consensus in the literature that frazil ice particles in saline water tend to be less adhesive and less likely to form flocs (Hanley and Tsang 1984, Kempema et al. 1993). Hanley and Tsang (1984) attributed this to the salt rejection as the ice forms creating a layer of higher salinity surrounding the ice crystals, thereby slightly reducing the freezing point around the individual crystals. This pocket of higher salinity depresses the freezing point around the frazil ice particle and therefore inhibits the ability of frazil ice particles to sinter together to form flocs. Kempema et al. (1993) described the orientation of the individual particles in saline water frazil flocs as aligned with their flat surfaces in contact. They also observed that the saline water flocs were smaller and had a more dendritic appearance than those produced in freshwater. The flocs also tended to stay in suspension until the experiment was stopped and the turbulence subsided.
Limited measurements have been made of the magnitude of supercooling in the oceans because it is challenging to measure supercooling in the field since salinity, temperature and pressure must be continuously measured. As frazil ice particles form, the salt is rejected, thus increasing the salinity of the surrounding solution and therefore, salinity is not constant throughout the process. Field measurements of oceanic supercooling include: 0.004 °C (Untersteiner and Sommerfeld 1964), 0.008 °C (Lewis and Perkin 1983) and 0.20 °C and 0.29 °C (Doronin and Kheisin 1975).

The purpose of this study is to investigate the properties of frazil ice particles in water at salinities ranging from 0 ‰ to 35‰ by using high-resolution digital images and advanced image processing techniques. Specifically, the study seeks to determine the effect on the properties of frazil ice as the salinity is increased.

2. Experimental Set-up and Methods

Experiments were performed in a frazil ice production tank in a cold room at the University of Alberta. Figure 1 provides an image of the overall experimental set-up. The tank is constructed of stainless steel and glass with base dimensions of 0.8 by 1.2 m, and the tank was filled to a depth of 1.2 m. The top of the tank was uncovered leaving the water surface exposed to the cold air temperatures. Turbulence was generated in the tank using four bottom-mounted propellers. The propellers were powered by NEMA 34 DC variable speed electric motors (278 W, 1.514N-m of torque, max speed 1750 rpm). Frazil ice particles were illuminated by a Genaray SpectroLED Essential 360 Daylight LED Light (3,200 lux at 1.0 m, 360 LED bulbs, 11.75” by 11.75”) that was placed on the far side of the tank. Directly opposite of the lights, two 10 × 10 cm square Cavision glass polarizing filters were mounted on the inside of the tank. The polarizers were spaced 2.2 cm apart and positioned flush to the glass on the near side of the tank. The polarizers were installed at 90° with respect to one another to cross-polarize the light passing through. A Sea-Bird SBE 39 temperature sensor (accuracy of 0.002 °C) and logger was used to record and monitor temperature in the tank during the experiments. The temperature sensor was placed approximately at the center of the tank. A space heater was positioned beside the camera blowing towards the glass parallel to the polarizers to prevent any frost formation on the glass.

A Nikon D800 with 36-megapixel resolution and equipped with an AF Micro-Nikkor 60 mm f/2.8D lens was used to capture the images. Preliminary experiments were performed to determine the settings that provided the best quality images. A summary of the camera settings used can be found in Table 1. The camera lens was positioned approximately 8.7 cm away from the glass of the tank for saline water experiments, resulting in an average pixel size of 8.3 μm. The lens was positioned approximately 5.7 cm away from the glass of the tank for fresh water experiments, resulting in an average pixel size of 6.4 μm. Therefore, the corresponding average measuring volume was 55.13 cm³ for saline water experiments and 33.07 cm³ for freshwater experiments. As such the ratio of saline water experiment volume to fresh water experiment...
volume is 1.67. This must be considered when comparing the number of frazil ice particles between the freshwater and salt water experiments.

For all experiments, the tank was filled to a depth of 1.2 m with fresh, filtered tap water. An Aqua-Pure AP110 filter with a filtration level of five microns was used to filter the tap water. The saline water was prepared at salinities of 15 ‰ and 35 ‰ by calculating and measuring the mass of Sifto Hy-Grade Food Grade Salt required. The upper limit of 35 ‰ was chosen because this is a typical salinity of seawater and of 15 ‰ was chosen to represent intermediate values that occur near salt and fresh water interfaces such as estuaries. The solution was then vigorously mixed with the propellers in the tank until the salt was completely dissolved. The salt that was used is specified to be predominantly sodium chloride (99.77% to 99.91% NaCl). The salt was added to the fresh, filtered water when the water temperature was approximately equal to 1 °C to ensure that the density of the water was consistent with that used in salinity calculations. Freshwater was periodically added to the tank to counteract evaporation and keep the depth and salinity constant.

The freezing point of the solution at varying salinities was also of interest so freezing point depression experiments were performed following the procedures developed by She et al. (2016). The experimental set-up for the freezing point depression experiments is presented in Figure 2. A 1000 mL sample from the frazil tank was gathered before each experiment. The water samples were stirred continuously using a magnetic mixer and the water temperature was monitored at 1 Hz using an RBR Solo temperature sensor (accuracy of ±0.002 °C).

For all experiments, the turbulence intensity was held constant by using a propeller speed of 325 rpm. The propeller speed was controlled using a dial and verified using a laser tachometer. The temperature sensor was programmed before each experiment to measure, log and provide a real-time readout of the water temperature. The cold room temperature was then set to -12 °C. Spatial and temporal variations in the air temperature were measured and logged throughout the experiments using both Mini Divers (accuracy ±0.1 °C) at frequency of 0.1 Hz and RBR Solos (accuracy ±0.002 °C) at a frequency of 1 Hz. The air temperature sensors were placed near the water surface, where the majority of the heat loss is assumed to occur. Throughout all experiments, it was determined that when the cold room was set to -12 °C the average air temperature at the water surface was approximately -8 °C. The cold room enters specifically timed defrost cycles throughout the day; experiments were timed to avoid entering a defrost cycle during supercooling and ice production.

A clear plastic ruler was placed in between the two polarizers using a spacer to ensure that the ruler was placed at the midpoint. The camera was then focused manually using the numbers and markings on the ruler. Images of the ruler at the midpoint, back and front were captured, which would later be used to determine a scale for the images. Ten background images were captured
before each experiment. The camera was programmed to capture images at a frequency of 1 Hz for a duration 1998 s and 999 s for the saline and freshwater experiments, respectively. For each experiment, the camera was started before the time that the water reached its freezing point for a given salinity. This ensured that the entire supercooling process was captured in the images. A total was 981 images were processed for each experiment which corresponds to about 16 minutes and 20 seconds of time past the freezing point.

3. Data Analysis

3.1 Image Processing

Images from each experiment were analyzed using an image processing algorithm developed by McFarlane et al. (2015) to determine the frazil ice particle sizes. The series of images captured during a particular experiment were loaded into MATLAB, and the average of the background images were subtracted from the series of images. Each image was converted first to greyscale then to black and white, or “binary”. The binary images were then dilated and eroded to fill in any gaps in space. Each region of white space (representing a particle or floc) was then analyzed and key properties including the area, major axis length, centroid, minor axis length, perimeter and eccentricity were determined using built in MATLAB functions. For this study, only properties of individual frazil ice particles were quantified. When three-dimensional disc-shaped particles are observed in a two-dimensional image, they appear as circles, lines or, most commonly, ellipses depending on their orientation. Therefore, the properties of the imaged particles were compared to the properties of a fitted ellipse to see if the shape of the particle in the image approximately resembles an ellipse, indicating that the particle was approximately disc-shaped. If the ratio of the area of the particle to the theoretical area of an ellipse with same minor and major axis lengths is less than 0.9, the particle is rejected (i.e. it is identified as not being disc-shaped). Additionally, if the percent difference between the perimeter of the particle and the theoretical perimeter of an ellipse with same minor and major axis lengths is greater than 25% then the particle is rejected. Using these thresholds the image processing algorithm has been shown to identify 93% of disc-shaped particles correctly in freshwater experiments (McFarlane et al. 2015).

In the saline water experiments conducted in this study the algorithm was found to identify most individual dendritic or hexagonal shaped particles as elliptical as well. This is shown in Figure 3 where a raw digital image and the binary image created by the image processing algorithm are compared. Figure 3b illustrates which particles were accepted by the algorithm and which were rejected as not being elliptical in shape. Generally, the algorithm rejects larger flocs and identifies individual particles consistently. Occasionally, smaller flocs are identified as individual particles and irregular shaped individual particles are rejected. Therefore, resulting final size distributions will include disc and irregular shaped individual particles as well as a relatively small number of small flocs.
4. Results and Discussion

4.1 Freezing Point Depression and Supercooling

The temperature data recorded using the Seabird was analyzed to produce supercooling curves. The supercooling curves are plots of water temperature as a function of time during the period where the temperature drops below the freezing point, reaches its minimum and then increases to near its residual. Supercooling curves for freshwater are slightly different than those in saline water. This difference is particularly apparent during the time when the residual temperature is reached. For saline water the residual temperature will not be constant but will continue to decrease because as ice is continually produced the salinity of the water will increase as salt is rejected (Brescia et al. 1975). The supercooling curves were aligned at the time where the water reached the freezing point and plotted as shown in Figure 4. In general, the supercooling curves for the experiments at a given salinity aligned quite well, indicating that the experiments were producing repeatable results. Mair et al. (1941) developed a method whereby the linearly sloping portion of the supercooling curve (i.e. the residual) is extrapolated back to where it intersects the original curve. This method does not provide the exact freezing point, but has been shown to produce a value accurate to within a few percent.

The freezing point for freshwater with salinity 0‰ was assumed to be 0 °C. The average freezing point depression for salinities of 15‰ and 35‰ was determined to be −0.89 °C and −2.09 °C, respectively. The average minimum supercooling temperatures observed in the experiments for fresh, 15‰ and 35‰ salinity were found to be −0.0851 °C, −0.9675 °C and −2.1829 °C, corresponding to values of supercooling of 0.0851 °C, 0.0775 °C and 0.0929 °C, respectively. These observed values of supercooling fall within the range of previous field measurements from the ocean.

4.2 Frazil Ice Particle Properties

4.2.1 Qualitative Observations

The digital image sequences displayed in Figures 5 and 6 show the evolution of frazil ice particles and flocs over time in freshwater and 35‰ saline water, respectively. In Figure 5, almost all of the individual frazil ice particles in the images are perfect disc shapes, whereas in Figure 6 the individual frazil ice particles are a variety of shapes including disc, dendritic and hexagonal. It is also evident by comparing Figures 5 and 6 that the flocs observed in fresh water 5 are generally much larger than those formed in saline water.

4.2.2 Quantitative Results

The output data from the digital image processing algorithm was used to compute the mean and median particle size, the standard deviation and total number of particles and this data is provided in Table 2. McFarlane et al. (2015) reported a mean of 0.59 mm, and in this study a
mean of 0.61 mm was computed for the freshwater experiments. The average size for salinities of 15 ‰ and 35 ‰ was 0.55 mm. This value is smaller than the sizes of particles reported in previous studies for saline water. The mean and median both remained approximately constant as the salinity increased but the standard deviation decreased by 18% as salinity increased from 0 ‰ to 35 ‰. The data in Table 2 show that as the salinity increased, a significantly greater number of individual particles were detected in the images. One possible reason there are a higher number of individual particles observed in saline experiments is that the saline particles are less likely to form flocs. When observing the entire sequence of images, in fresh water it was evident that frazil ice particles tend to flocculate more quickly (see Figure 5) than in saline water and subsequently rise to the surface, resulting in fewer individual particles. In saline water, frazil flocs tend to remain suspended in the flow as can be seen in Figure 6.

In Figure 7 the size distributions of frazil ice particles at the three salinities are plotted along with lognormal distributions with the corresponding mean and standard deviation. For freshwater, the particle size distribution fits a lognormal distribution quite well except there is evidence of a secondary peak at sizes greater than 1 mm. The size distribution for the 15 ‰ case is skewed slightly to the left of the lognormal distribution, but otherwise it fits the lognormal distribution very well. Finally, for the 35 ‰ case, the processed data fits the lognormal distribution very closely. In all cases a lognormal distribution fits the measured particle size distribution reasonably well so this appears to be a suitable approximation for individual frazil ice particles in both saline water and fresh water.

5. Summary and Conclusions

Frazil ice was produced in the frazil ice tank and high quality digital images of the crystals and flocs were captured. Experiments were conducted at salinities of 0 ‰, 15 ‰ and 35 ‰ to determine the impact of salinity on frazil crystal size, shape and floc size. The high quality digital images were then processed using a digital image processing algorithm that analyzed the images to determine the sizes of individual frazil ice particles. The results showed that the average size of individual particles in freshwater and saline water were very similar at 0.61 mm and 0.55 mm, respectively. The particle size distributions of all experiments fit a lognormal distribution very well. The data showed that the largest number of individual particles was recorded for a salinity of 35 ‰, and the fewest particles were recorded in fresh water. It was observed that in the freshwater experiments larger flocs tended to be produced compared to the saline water experiments. Additionally, the fresh water frazil ice crystals tend to be predominantly discs, whereas the saline water experiments produced more irregularly shaped particles including dendritic and hexagonal shapes.

In the future, we seek to support our qualitative observations with quantitative evidence. The image processing algorithm will be modified to distinguish irregular shaped particles from disc-
shaped particles. Furthermore, the effect of salinity on the properties of frazil flocs will be investigated.

References


Ushio, S., and Wakatsuchi, M. 1993. A laboratory study on supercooling and frazil ice
production processes in winter coastal polynyas. 98(93): 321–328.
Ye, S.Q., Doering, J., and Shen, H.T. 2004. A laboratory study of frazil evolution in a counter-
rotating flume. Canadian Journal of Civil Engineering, 31(6): 899–914. doi:10.1139/l04-
056.

Table 1. Summary of camera settings for each experiment.

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<th>Setting</th>
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<th>Freshwater</th>
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<td>Aperture</td>
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<td>f/25</td>
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<td>Image Frequency (Hz)</td>
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<td>Camera Distance (cm)</td>
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Table 2. Summary of frazil ice properties at three salinities.

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<th>Salinity (%o)</th>
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<th>Median Size (mm)</th>
<th>Standard Deviation (mm)</th>
<th>Total Number of Particles</th>
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<td>716254</td>
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*Adjusted by factor of 1.67 to account for smaller field of view for freshwater experiments.
Figure 1. Image of the frazil ice tank experimental setup.

Figure 2. Image of freezing point depression experimental setup.
Figure 3. a) Original image captured in 35 ‰ salinity water and b) modified binary image illustrating frazil ice particles identified as approximately disc-shaped (white in color) and particles identified as being irregularly shaped (grey in color).
Figure 4. Time series of water temperature showing the supercooling curves for various salinities.
Figure 5. Frazil ice images in freshwater at various stages of supercooling. Images were taken at ~1 min intervals starting at $t = 8$ min after the start of supercooling.
Figure 6. Frazil ice images in 35‰ saline water at various stages of supercooling. Images were taken at ~ 1 min intervals starting at $t = 8$ min after the start of supercooling. These images were resized to be shown on the same scale as freshwater images.
Figure 7. Particle size distribution for various salinities