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Effect of Turbulence Intensity on Frazil Flocculation and Secondary Nucleation

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The processes of secondary nucleation and flocculation of frazil ice are relatively poorly understood. In order to better understand the effect that turbulence intensity has on these processes, a series of experiments were undertaken at the Hydraulics Research & Testing Facility in the University of Manitoba using a counter-rotating flume.

Five sets of bed plates ranging in roughness from smooth PVC to 20 mm gravel were used to generate the turbulence in the flume. Velocity measurements in open water were made using a constant temperature anemometer with a conical hot-film probe. The ability to rotate the flume walls at any given rate enabled the researchers to perform experiments where the average velocity was kept constant, while the turbulence intensity increased with increasing bed roughness.

Measurements of water temperature, air temperature, and digital images taken during ice formation were analyzed. It was found that the rate of secondary nucleation increased with increasing turbulence intensity, however, the trend was not well defined. A multiple linear regression model using turbulence intensity in addition to the maximum degree of supercooling as the two independent variables was found to reasonably model the rate of secondary nucleation. Initial results demonstrate that turbulence intensity increases the uniformity of the vertical distribution of frazil particles and tends to inhibit frazil flocculation.

1. Introduction

The numerous negative effects associated with frazil formation have significant economic repercussions. In Manitoba, trash rack blockages and anchor ice formation downstream of hydroelectric generating stations are the two most costly events. Despite the economic forfeiture and the motivation that this provides for further research into the fundamental properties of frazil ice, many frazil ice processes are poorly understood. This paper endeavours to present the results from a set of experiments conducted at the Hydraulics Research & Testing Facility at the University of Manitoba. In particular, the effects of turbulence intensity on the processes of secondary nucleation and flocculation will be presented.

2. Background

Experimental studies on frazil formation have been conducted in the past, however, the number of such studies is relatively limited. Michel (1963) conducted many frazil ice experiments in an outdoor recirculating flume at Laval University in Quebec. The discharge and flow speed was generated with an impeller. Average velocities ranged from about 0.15 m/s to 0.55 m/s. Carstens (1966) studied frazil ice in a cold room using an oval recirculating flume whose flow was generated using a variable speed propeller that was slightly inset to the flume bottom. Velocities between 0.33 and 0.7 m/s were reported, and it was noted that while the velocity distribution was not as even as a rectangular channel, it did become fairly uniform at the end of the straight sections. Other experiments have been conducted in circular tanks driven by paddles (Hanley and Michel 1977), rectangular tanks with turbulence generated by stirrers (Tsang and Hanley 1985), and turbulence jars (Ettema *et al.* 1984). A summary of the earlier frazil ice research can be found in the monographs by Daly (1984, 1994), Ettema *et al.* (1984), and Tsang (1982).

Many of these experimental studies did not report quantitative measurements of any turbulence parameters, however, Daly (1994) estimated the turbulent energy dissipation rate for the tests from several of the aforementioned authors. Ettema *et al.* (1984), whose experimental apparatus used an oscillating grid to generate turbulence, deduced the turbulent momentum exchange rate through measurements of the concentration of suspended 0.1 mm diameter sand. They concluded that the rate of frazil formation increased with increasing turbulence intensity and that at higher turbulence intensities a limiting size of frazil ice particles was reached. Size distributions were not measured during these experiments.

2.1 Secondary Nucleation

Initial frazil ice nucleation has been generally accepted to occur due to a mass-exchange process (Osterkamp, 1978). However, this does not explain the observed rapid proliferation of frazil ice in both the field and the lab. The process of secondary nucleation refers to the formation of frazil ice with other ice particles being the nuclei. These nuclei have been suggested to form due to collisions with solid objects, collisions with other ice particles and due to fluid shear causing particle breakage. As might be expected, the number of nuclei produced in a given collision increases as the energy of the collision increases (Clontz and McCabe, 1971). Frazil ice has also been shown to form dendrites which could be especially susceptible for breakage. One can imagine that a single crystal collision forms several nuclei, which in turn causes several more collisions. This process could easily explain the impressive rate at which frazil ice has been observed to form.

Several papers regarding frazil ice nucleation in batch crystallizers, such as that by Evans et al. (1974) demonstrate that turbulence intensity within the water body promotes crystal-crystal collisions, which in turn creates nuclei for further frazil ice production. Lal *et al.* (1969) put forth a theory (termed the 'survival theory') and a corresponding equation to estimate the critical radius. Particles smaller than the critical radius were assumed to melt, while those larger than the critical radius would survive and begin to grow. This critical radius is a function of the degree of supercooling, in that colder water will allow smaller particles to survive. One can hypothesize that if colder water will allow more of the nuclei generated from collisions to survive, this will generate a greater number of particles and therefore increase the rate of secondary nucleation. The experimental results from Ettema *et al.* (1984) seem to support these two separate driving factors of secondary nucleation. They concluded that the rate of secondary nucleation increased with increasing turbulence intensity and colder water temperatures.

2.2 Flocculation

Frazil particles sinter together, meaning that they collide and an ice bond is formed at the contact point, fusing them together. Mercier (1984) used turbulent shear and differential rising to explain how particles come into contact with each other for sintering. For disks of thickness on the order of 1 – 10 μm, Martin (1981) stated that bonds could form in a time on the order of 10^{-2} seconds. Since the most stable shape is a sphere, the point where two discs connect is very unstable and the chemical potential gradient causes ice to bridge the gap between them (Mercier, 1984). A floc can be defined as a group of particles that have sintered together. The buoyant force from these flocs causes them to float to the surface where they can then accumulate to become surface slush or frazil pans. Many previous experimental frazil ice studies did not have the ability to observe frazil flocculation either due to the method of turbulence generation (*i.e.* oscillating grids or paddles), or because of the pumps necessary to recirculate the flow.

3. Experiments

The research reported herein was conducted using the counter-rotating flume located in the Acres Manitoba Hydraulics Research & Testing Facility at the University of Manitoba. A description of the flume can be found in Clark and Doering (2006), and a schematic can be seen in Figure 1. The flume consists of an annular channel with a centerline diameter of 1.2 m, a width of 0.2 m and a water depth up to 0.35 m. The bed and walls are mounted independently, which allows them to rotate in opposite directions. The bed can be lined with plates fixed with any desired gravel size.

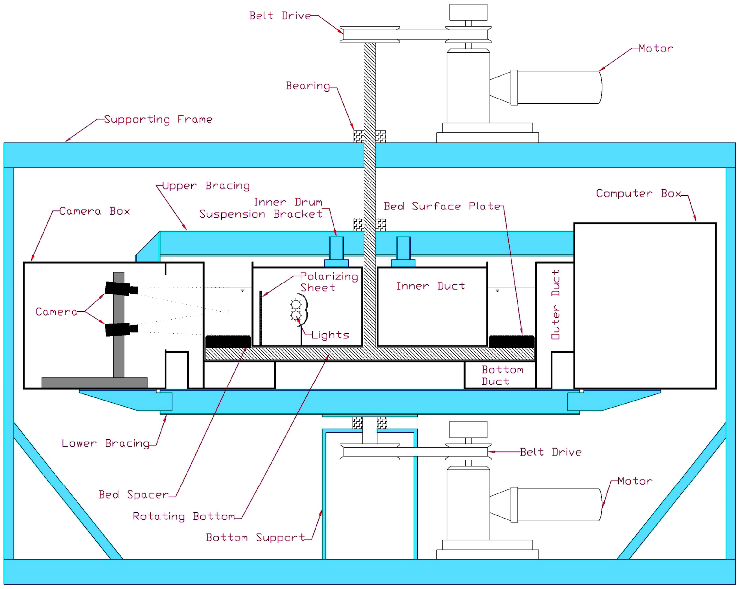

Figure 1: Schematic of the counter-rotating flume.

The objective of this most recent set of experiments was to determine the effects of turbulence intensity on the formation and evolution of frazil ice. Five sets of bed plates ranging from PVC roughened with a random orbital sander to 20 mm diameter gravel were used to generate different levels of turbulence for a constant volume of water in the flume and a constant bed rotation rate. Prior to conducting experiments to observe ice formation it was necessary to conduct a series of experiments to quantify the turbulence level in the flume for each set of plates and corresponding bed and wall rotation rate. A very brief overview of some of the bulk parameters from these velocity measurements can be found in Clark and Doering (2006). For convenience they are presented in Table 1.

Table 1: Summary of hydraulic conditions of experiments.

Gravel Diameter [mm]	**Bed Speed [cm/s]**	**Wall Speed [cm/s]**	$\overline{U}$ **[cm/s]**	**u'**
0.0	60	41	75	0.0203
1.7	60	52	77	0.0240
3.4	60	59	75	0.0273
10.0	60	68	73	0.0387
20.0	60	85	76	0.0408

A set of 23 experiments was conducted in total. Each of the 5 sets of bed plates was used with the corresponding volume-adjusted water levels and wall rotation rates that were reported in Table 1. Since it was desired to isolate turbulence intensity as the variable to be tested, the room temperature as well as the inner, outer, and bottom duct temperatures of the flume were kept constant for the entire set of experiments.

Throughout the experiments water temperature was measured every two seconds using a Hart Scientific – Black Stack Thermistor. When the water temperature reached approximately 0.05°C two cameras began taking images of nearly the entire water column. Images were acquired on a duty cycle, where 30 images were acquired at a frequency of 2 Hz, after which there was a 45 s delay prior to the next cycle of images. These images were acquired until approximately 10 minutes after the water temperature reached its level of residual supercooling. Further details regarding the data acquisition procedures can be found in Clark (2006).

4. Results

Image analysis was performed using digital image processing algorithms developed with the aid of the Matlab Image Processing Toolbox. Compete details regarding this procedure can be found in Clark (2006). The temperature data was sufficiently accurate and precise that no filtering or manipulation of any kind was required.

4.1 Secondary Nucleation Inferred From Temperature Data

The effects of this rapid increase in the number of frazil particles were observed in both the water temperature and image data. For each experiment the water cooled at a constant rate, dropped below 0°C, and then began to warm up. This warming of the water was caused by the latent heat of fusion released from newly formed frazil ice particles. For this reason the warming rate of the water provided an indirect indication of the rate of secondary nucleation. After the water temperature reached its maximum degree of supercooling the rapid increase in water temperature was caused predominantly by the secondary nucleation process.

After measuring the warming rates for all experiments, the data was plotted against the appropriate turbulence intensity, since it was hypothesized that higher turbulence levels would result in more collisions and hence a more rapid rate of secondary nucleation. The R^2 value of this plot was 0.56, and a clear trend was not present. The warming rate data was then plotted against the maximum degree of supercooling during the respective experiment, and again a clear trend was not present. Finally, a multiple linear regression model using turbulence intensity and maximum degree of supercooling as the independent variables was used. Figure 2 shows the results of plotting the predicted warming rate using this multiple linear regression model versus the measured warming rate. A 45° line has been superimposed on the data to help illustrate that the scatter seems to be uniformly distributed about the line, and a clear trend is apparent. Furthermore, statistical tests demonstrate that both independent variables are statistically significant to the 95th percent confidence level.

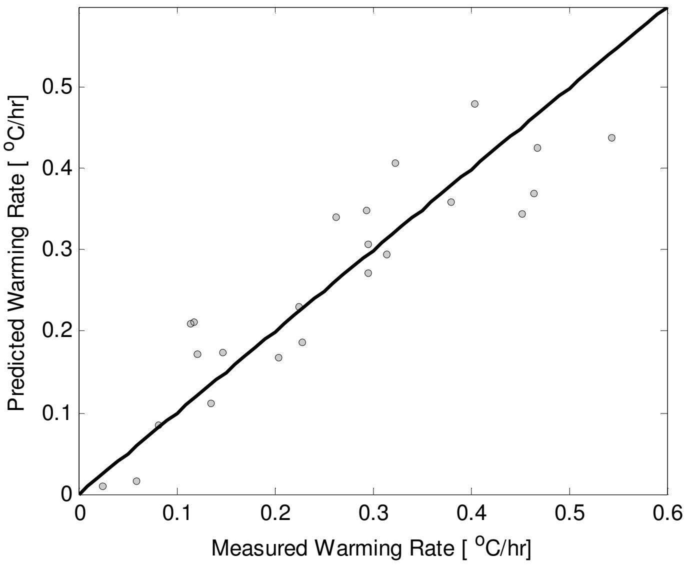

Figure 2: Comparison of measured and predicted warming rates.

4.2 Secondary Nucleation Inferred From Temperature Data

A more direct measurement of the rate of secondary nucleation can be determined using the images taken throughout each experiment. The number of clear disk-shaped frazil particles for each cycle of images was normalized by the peak number of particles within that particular experiment. This data was then plotted against time, as shown in Figure 3. A nearly linear rate of increase in the number of particles was observed between the region of 10% to 90% of the peak number of particles. It was this region of the data that was used to determine the rate of secondary nucleation using Equation 1.

$$\dot{n}_s = \frac{0.8(Peak\,\#\,Particles)}{t_{10-90}} \bullet \frac{1}{\forall \cdot 60} \qquad [1]$$

where $\forall$ was the estimated representative volume of each image given by multiplying the size of an average pixel by the resolution of the camera (1200*1024) and using a 0.05 m depth of field. The rate was divided by 60 to make the units of $\dot{n}_s$ equal to particles per cubic meter per second. It should be noted that by attributing the rate of increase of the number of particles to secondary nucleation it has been assumed that the rate of nucleation via mass transport processes is both constant with time as well as significantly less than the rate of secondary nucleation.

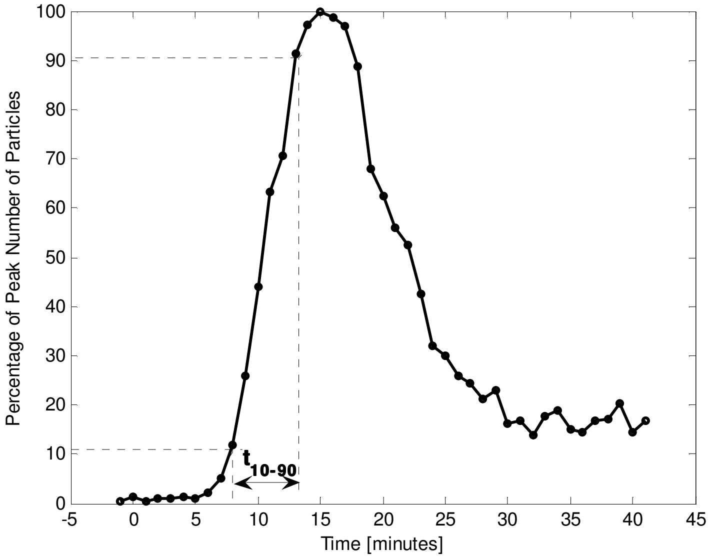

Figure 3: Temporal variation of the normalized number of clear disk-shaped particles.

The values of the secondary nucleation rate were then plotted against turbulence intensity, and a coefficient of determination of 0.48 was found. A clear trend was not apparent. Once again a multiple linear regression model with turbulence intensity and maximum degree of supercooling was used to model the rate of secondary nucleation. A plot of the predicted versus measured rate of secondary nucleation is shown in Figure 4. Despite some scatter, one can notice that the data seems to be uniformly distributed about the superimposed 45° line, and a trend is quite visible. As with the warming rate, both independent variables were shown to be statistically significant.

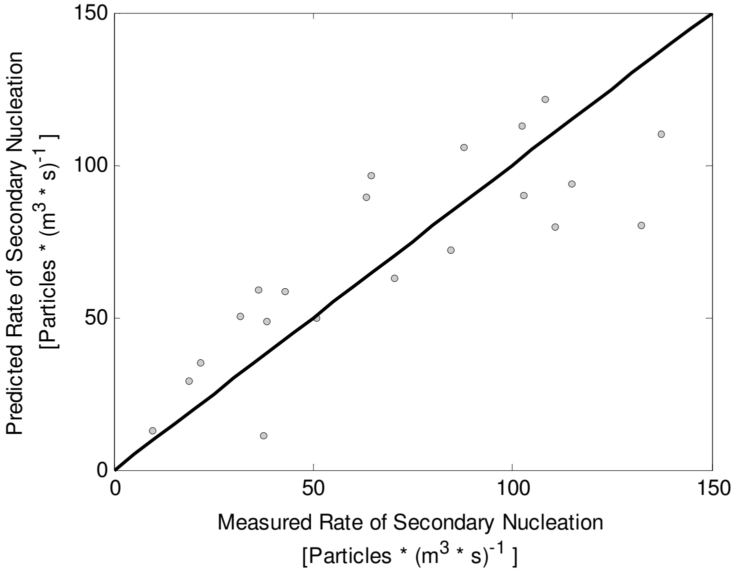

Figure 4: Comparison of measured and predicted rates of secondary nucleation.

4.3 Vertical Distribution

The vertical distribution of frazil particles throughout an experiment was analyzed using the digital images. Of particular interest was the effect of turbulence intensity on this distribution. The reader should be reminded, however, that the one dimensional probe used to measure turbulence intensity in this study did not measure the vertical component of velocity, which is likely the most significant with regards to the vertical distribution of frazil particles. This shortcoming notwithstanding, an attempt was made to qualitatively study these effects.

The data from the period beginning five minutes before the peak number of particles, and extending five minutes after the peak was used. This data set included the size of all clear frazil particles, regardless of there shape. Five different bin sizes were selected, ranging from sizes that are likely to be single particles, to that which is much more likely to be a frazil floc. Based on the location of the centroid of the detected particles, Figure 5 presents the vertical distributions of five separate experiments. The top row of distributions corresponds to the lowest turbulence intensity, with the turbulence intensity increasing to its maximum value in the bottom row. Within the individual graphs, the total number of observations as well as the percentage of the total number of particles that were in that particular size bin are noted. As expected, the vertical distributions appear more uniform for the higher turbulence intensities and smaller particle sizes.

4.4 Flocculation

A brief study of the effect of turbulence intensity on the process of flocculation was also undertaken, the results of which are presented in Figure 6. Each graph in this figure includes the supercooling curve for the experiment, as well as the number of frazil flocs that were observed in each cycle of images. In the development of this figure a floc was considered to be any particle with an equivalent diameter greater than 17 mm. The two cameras were placed vertically, with camera 1 on the top and camera 2 below it. The field of view for each camera roughly cut the water depth in half. Figure 6a corresponds to an experiment with the lowest turbulence intensity, with turbulence intensity increasing alphabetically up to the maximum value in Figure 6e.

Several observations can be made from this figure. First of all, one can note that the number of flocs detected with camera 1 without exception exceeds the number of flocs in camera 2. This is not unexpected, since the buoyant force exerted on these flocs tends to cause them to move towards the water surface. Secondly, and perhaps more importantly, the number of observed frazil flocs decreases with increasing turbulence intensity. In fact, at the largest value of turbulence intensity there are virtually no frazil flocs greater than 17 mm in diameter that were observed.

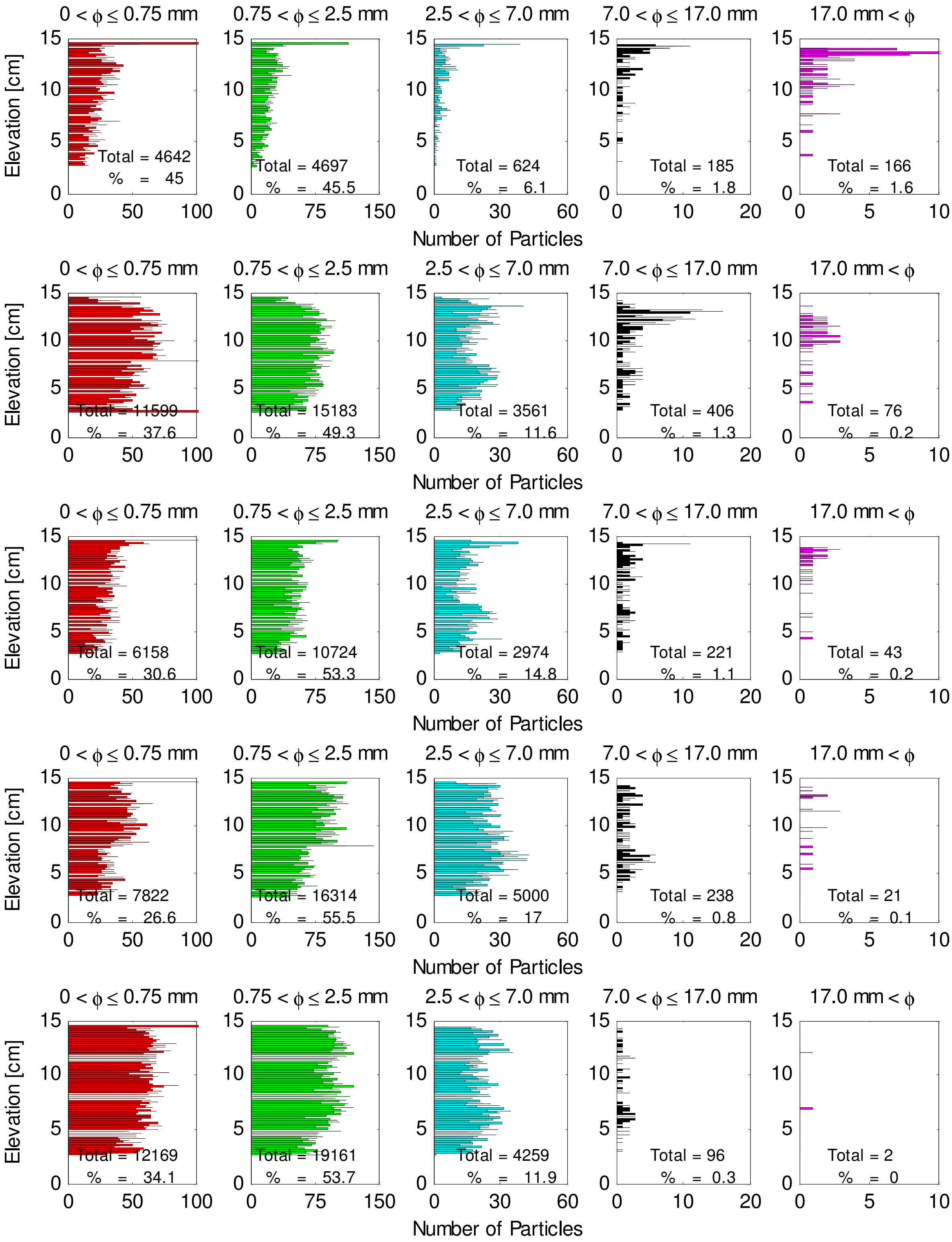

Figure 5: Vertical distribution of frazil particles of various size ranges for 5 levels of turbulence intensity. From top row to bottom row: u' = 0.020, 0.024, 0.027, 0.033, 0.041.

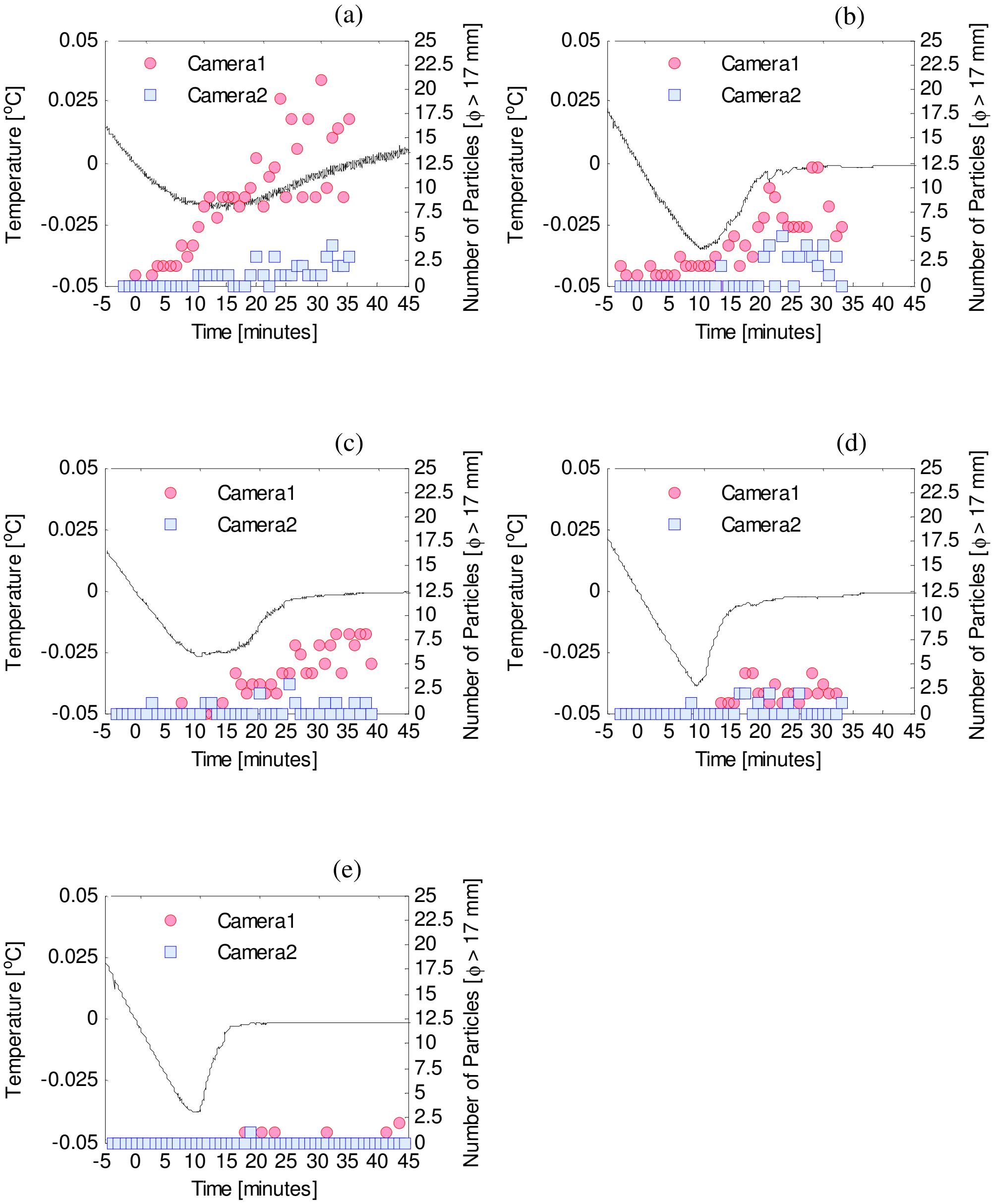

Figure 6: Variation of the number of frazil particles greater than 17 mm in diameter with time for the top and bottom cameras. The respective turbulence intensities are: (a) 0.020; (b) 0.024; (c) 0.027; (d) 0.033; and (e) 0.041.

5. Conclusions

The results of this study support the previous findings of Ettema *et al.* (1984) which conclude that both turbulence intensity and the maximum degree of supercooling affect the rate of secondary nucleation. This is important for at least two reasons. The turbulence jar used by Ettema *et al.* used an oscillating grid to generate turbulence, which may cause some to question its applicability to open channel flow. For that matter, some may question the apparatus used in this study as well, however, the author would contend that it provides a reasonable approximation to open channel flow. Secondly, the results and trends from Ettema *et al.* are less clear at low values of maximum supercooling on the order of that which is generally observed in the field. The current study concentrates only on this range of supercooling, thereby confirming the trends that were previously noted. Furthermore, the current study was able to use image data in addition to temperature data to make these conclusions.

Vertical distributions of frazil particles were shown to qualitatively demonstrate that higher turbulence levels cause a more uniform vertical distribution, notwithstanding the fact that longitudinal rather than vertical velocities were measured. A more in-depth look at this data would likely have been warranted if in fact vertical turbulence intensity had been measured, as it would have been interesting to look at the relationship between the measured particle diameter, the calculated buoyant force, and the measured turbulence intensity at the observed particle location in the depth of flow.

Measurements of the variation of the number of frazil flocs with time for five different levels of turbulence intensity provide data to support the conclusion that turbulence intensity tends to inhibit the formation of frazil flocs. It is hypothesized that the turbulent kinetic energy in the associated eddies and vortices within the flume physically limits the size of frazil flocs. This is somewhat counter-intuitive when one considers the fact that a higher turbulence intensity likely increases the number of particle-particle collisions, thus providing more opportunities for floc formation at higher turbulence levels.

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