EFFECT OF TURBULENCE INTENSITY ON FRAZIL FORMATION

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ABSTRACT
In order to better understand the effect of turbulence intensity on frazil formation and evolution 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 roughened PVC to 20 mm gravel were used to generate turbulence in the flume. Velocity measurements 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 virtually constant, while the turbulence intensity increased with increasing bed roughness.

Measurements of water and air temperature as well as digital images taken during ice formation were analyzed. It was found that although turbulence intensity seemed to have an effect on several of the key features of a supercooling curve, the relationships were not particularly strong. The most significant finding is the mean diameter and standard deviation of the frazil disks seem to reach nearly constant values after several minutes of supercooling, and that these values were strongly affected by turbulence intensity. In addition, it is hypothesized that a power-law relationship could describe the variation of the mean diameter and standard deviation with time.

KEYWORDS: Frazil ice; Turbulence intensity; Particle size distributions.
INTRODUCTION
The negative effects caused by frazil ice have serious economic repercussions every year. Hydroelectric generating stations can become fully obstructed, channels can become blocked, as can water supply intakes. Anchor ice formation downstream of a generating station can decrease the net operating head resulting in a reduction of output capacity. These negative impacts fuel the ongoing research into frazil ice formation and evolution.

A handful of experimental studies on frazil formation have been conducted in the past. Michel (1963) conducted many frazil ice experiments in an outdoor recirculating flume at the 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).

The research reported herein was conducted using the counter-rotating flume located in the Hydraulics Research & Testing Facility at the University of Manitoba. A description of the flume can be found in Clark and Doering (2006). Briefly, 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.

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 determine the wall rotation rate that would minimize the secondary circulation in the flume for each of the sets of bed plates. In addition it was necessary to quantify the turbulence level in the flume for each set of plates.

VELOCITY MEASUREMENTS
A series of experiments was undertaken to determine the velocity and turbulence intensity distributions in the counter-rotating flume. For a given bed rotation rate and gravel diameter a trial and error procedure was used to determine the corresponding wall speed that would minimize the secondary circulation in the flume for each of the five sets of bed plates used in the experiments. It was found that this wall speed caused an average velocity relative to the channel bed of approximately 0.75 m/s for each set of bed plates. The water depth was set to 0.15 m for the set of roughened PVC bed plates, and the volume of water in the flume was increased by an
amount equal to the volume of gravel for each additional set of plates. This was done to ensure that the total volume of water remained constant for each experiment.

Velocity was measured using a one-dimensional hot-film constant temperature anemometer equipped with a conical probe. The sampling rate was 1000 Hz for a period of 60 seconds, and the overheat ratio was set to 12.5%. The water temperature was kept constant to within approximately 0.02°C throughout an experiment. A shop-built traversing mechanism allowed the water velocity to be measured along nine vertical profiles consisting of nine or ten measurement points each. An average velocity and turbulence intensity was calculated for the flume cross-section. Turbulence intensity was calculated using the equation

\[ u' = \frac{1}{U} \left( \frac{1}{n+1} \sum_{i=1}^{n} (u_i - \overline{U})^2 \right)^{0.5}, \]

where \( u' \) is the turbulence intensity, \( u_i \) is the instantaneous velocity and \( \overline{U} \) is the average velocity. Table 1 summarizes the results of these experiments. Note that as expected the turbulence intensity increases with increasing gravel diameter.

<table>
<thead>
<tr>
<th>Gravel Diameter [mm]</th>
<th>Bed Speed [m/s]</th>
<th>Wall Speed [m/s]</th>
<th>( \overline{U} ) [m/s]</th>
<th>( u' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.6</td>
<td>0.410</td>
<td>0.752</td>
<td>0.0203</td>
</tr>
<tr>
<td>1.7</td>
<td>0.6</td>
<td>0.525</td>
<td>0.766</td>
<td>0.0240</td>
</tr>
<tr>
<td>3.4</td>
<td>0.6</td>
<td>0.590</td>
<td>0.752</td>
<td>0.0273</td>
</tr>
<tr>
<td>10.0</td>
<td>0.6</td>
<td>0.680</td>
<td>0.731</td>
<td>0.0387</td>
</tr>
<tr>
<td>20.0</td>
<td>0.6</td>
<td>0.850</td>
<td>0.757</td>
<td>0.0408</td>
</tr>
</tbody>
</table>

It can be noted that no attempt was made to measure the turbulence intensity in the flume during an experiment involving ice formation due to the delicate nature of a hot-film probe.

**ICE EXPERIMENTS**

Once the turbulence intensity had been determined using the aforementioned measurements a set of 23 experiments was conducted to determine the effect of turbulence intensity on various aspects of frazil ice formation and evolution. Each of the five sets of bed plates was used with the corresponding volume-adjusted water levels and wall rotation rates. Four or five experiments for each bed plate were performed. 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 all experiments. One experiment was conducted each day, and the room and water temperature was allowed to warm up to approximately 1°C overnight. The experiments were conducted over a period of approximately 2 months. The
results from these experiments can be divided into two categories based on the data acquisition method: results obtained from temperature data and results obtained from the image data.

**Temperature Measurement Results**

For a given supercooling curve as shown in Figure 1 several key features can be identified and labeled. The definitions of the cooling rate and minimum temperature $T_{\text{min}}$ are self-explanatory, while the time of principal supercooling $t_{sp}$ needs to be defined as the time it takes for the water to drop below 0°C, reach $T_{\text{min}}$, and then rise back to its residual temperature $T_r$. Figure 1b shows that higher levels of turbulence seem to cause shorter periods of principal supercooling. Figure 1c shows that the effect of turbulence intensity on the minimum temperature $T_{\text{min}}$ seems to be relatively minor, while Figure 1d shows that higher levels of turbulence intensity cause the water to cool more rapidly. The scatter in the experimental data leads the authors to believe that while turbulence intensity does in fact seem to affect some aspects of the supercooling curve, these relationships do not appear to be particularly strong.

![Graphs showing temperature and turbulence intensity relationships](image)

**Figure 1.** (a) A typical supercooling curve. Effect of turbulence intensity on: (b) the principal period of supercooling, (c) the minimum temperature, and (d) the cooling rate.
**Image Analysis Results**

Images were captured with a monochrome Hitachi KPF-100A ccd camera as summarized in Clark and Doering (2006). The average field of view was a 6.7 by 5.7 cm rectangle with a top edge approximately 0.5 cm from water surface. A duty cycle was used whereby images were acquired at a rate of 2 Hz for 15 seconds and then paused for 45 seconds. This process began a few minutes prior to the water becoming supercooled and continued for approximately one hour on average. Image analysis was conducted using a Matlab algorithm similar to that described by Doering and Morris (2003), the main difference being that an edge detection algorithm based on the Canny method was used. Since disk-shaped particles appear anywhere from circular to elliptical depending on their orientation at the time of image acquisition, an additional algorithm was used to classify the particles as either ‘elliptical’ or ‘other’. This allowed further analysis to focus on single disk-shaped particles rather than oddly shaped particles or those which had already started to flocculate together.

After classifying the detected particles in every image for a given experiment as either ‘elliptical’ or ‘other’, the elliptical particles in each cycle of the experiment were grouped together and their characteristics were analyzed. Of particular interest was determining the mean and standard deviation of the particles and the shape of the particle-size distribution. Previous research by Daly and Colbeck (1986) as well as Clark and Doering (2004, 2006) show that a lognormal distribution cannot be rejected in describing the shape of the particle-size distribution. This set of experiments also supports this assertion. With this information, the next objective was to determine how the mean and standard deviation of the distribution changes with time. Clark and Doering (2006) observed that the mean particle diameter seemed to reach a nearly constant value after some period of time. The current series of experiments was used to determine what effects turbulence intensity may have on the size distribution as well as this total mean elliptical particle diameter.

For each experiment the mean and standard deviation of the entire set of detected elliptical particles was calculated. This data is shown in Figure 2 plotted against turbulence intensity. For both the mean and the standard deviation it can be seen that turbulence intensity causes an increase until some peak value where the turbulence seems to physically limit the size of the frazil particles. A third-order polynomial has been fit to the data and seems to reliably predict the mean and standard deviation for a given value of turbulence intensity in the tested range.
Figure 2. Effect of turbulence intensity on the total mean and standard deviation of the detected elliptical frazil particles.

While this relationship describes the total mean and standard deviation, it does not offer any direct insight into the variation of the mean and standard deviation of the particles with time. Figure 3 shows the data from one experiment with a turbulence intensity of 0.024. It can be seen that both the mean and standard deviation increase over time and tend towards a plateau where they either remain constant or increase at a relatively slow rate, albeit with a fair amount of scatter. It should be mentioned that since the total number of particles per cycle increases over time throughout the supercooling process the first few points in the figures are averages of fewer observations than those at middle and latter part of the experiment. Superimposed on the data are two power-law curves of the form

\[ \mu(t) = a t^b \]  

and

\[ \sigma(t)^2 = c t^d, \]  

where \( \mu \) is the mean, \( \sigma^2 \) is the standard deviation and \( a, b, c, d \) are constants. Time is denoted by \( t \), with \( t = 0 \) defined as the point where the temperature first drops below 0°C. Note that the curves are offset slightly to the right, presumably to the time of initial nucleation.
Although the experimental data exhibits some scatter, the given curves seem to make a reasonable approximation of the variation of both the mean and standard deviation. One method to test this would be to compare the histogram of the measured particle diameters for each cycle to the lognormal distribution whose mean and standard deviation can be described with the above equations. One such curve is shown in Figure 4. It can be seen that at time $t = 21$ minutes the predicted mean and standard deviation make a very reasonable approximation of the measured data.

One should be reminded of the short-comings of the experimental procedure used. First, the field of view of the camera causes the size of one pixel to be 56 $\mu$m. In an attempt to avoid detecting noise as particles, the current algorithm requires that a particle consist of at least 4 pixels. If one combines this information with the measurements of frazil particles made by Daly and Colbeck (1986) who measured particles as small as 36 $\mu$m, as well as the commonly accepted survival theory which predicts the smallest frazil particles to be on the order of 4 $\mu$m, one can conclude that there are certainly frazil particles that have been omitted from the current analysis. Second,

**Figure 3.** Variation of the mean and standard deviation of elliptical particles for an experiment with $u' = 0.024$. 
it has been mentioned that the total number of particles near the beginning of the experiment is relatively small. The combination of these two facts leaves opportunities for future work.

![Comparison of measured particle-size distribution to lognormal distribution](image)

**Figure 4.** Comparison of the measured particle-size distribution to the lognormal distribution with \( \mu \) and \( \sigma^2 \) given by the aforementioned power-law.

It is anticipated that by combining the results summarized in Figure 3 with the given power-law equations one would be able to develop an equation to describe the variation of the mean and standard deviation as a function of both time and turbulence intensity.

**CONCLUSION**

Velocity measurements have allowed the wall rotation rate of the counter-rotating flume to be calibrated for a given bed speed and volume-adjusted water level for five different bed plates of varying gravel diameter to reduce secondary circulation. This has allowed the turbulence intensity in the flume to be isolated as a variable to be tested for its effect on the formation and evolution of frazil ice. It has been found that the total mean and standard deviation of the elliptical frazil particles increases with increasing turbulence intensity until a point where the level of turbulence seems to physically limit the size of the particles. Despite not being able to measure the very small frazil particles it has been shown that a power-law seems to fit the data reasonably well. Future work will focus on developing an equation to describe the variation of the mean and standard deviation as a function of both time and turbulence intensity.

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**REFERENCES**


