



## **Laboratory Measurements of Frazil Ice Rise Velocity**

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The rise velocity of frazil ice particles remains a relative unknown in understanding the river freeze-up process. Current numerical models use a number of different techniques for simulating the frazil rise process in lieu of precise data. Experimental studies carried out in the past have collected data for particles rising at many different velocities, but have been unable to relate these velocities to an accurate measure of the particle diameter.

In this study frazil ice particles were captured in a series of high resolution digital images as they ascended between two cross-polarizing filters. These images were then analysed using an image processing algorithm that accurately computes the diameter of each particle, and tracks the movement of the centroid of each particle from one image to the next to determine the particle rise velocity. Particles 0.24 to 2.92 mm in diameter were observed rising at velocities ranging from 0.40 to 13.05 mm/s and all of the data could be enveloped by theoretical solutions corresponding to particle diameter to thickness ratios of 2 and 80.

## 1. Introduction

Ice process modeling is an important and increasingly prevalent tool in river ice engineering. For many stages in the formation and evolution of river ice however, there is little or no available data for validating these models. In particular, when modeling freeze-up, data describing surface ice characteristics such as the rate of ice front progression is often all that is available. Additional data such as surface ice concentrations of individual pans and rafts may also exist, but only in the best case scenarios. A critical stage of the freeze-up process occurs prior to the appearance of significant quantities of ice at the water surface, and the temporal and spatial dynamics of this stage depend to a large extent on the rise velocity of frazil ice particles. Without validation data for this early stage of ice cover development however, it is impossible to know if the models are really getting it right, or if the errors in these components are simply cancelling each other out. This research is focused on addressing this problem by through the study of frazil ice rise velocity.

A logical first step in improving our understanding of the physics of rising frazil ice particles in rivers is to study the rise velocities of individual particles in quiescent water; however, very few researchers have attempted this to date. Gosink and Osterkamp (1983) scooped frazil ice particles out of a river with a graduated cylinder and estimated rise velocities by timing the particles with a stop watch. One disadvantage of their method was that particles diameters were only estimated to the nearest 0.5 mm using the cylinder graduations for a scale. They also noted that some residual turbulent motions were occasionally observed and, in a few cases, smaller discs appeared to be accelerating in the wake of a larger disc, which may have impacted their measurements. In addition to their experimental observations Gosink and Osterkamp (1983) also developed a theoretical expression to predict a particle's rise velocity using a simple force balance between the form drag and the buoyant force acting on a horizontal disc, shown in Equation [1],

$$\rho_i \pi \left( \frac{d^2}{4} \right) t a = (\rho_w - \rho_i) \pi \left( \frac{d^2}{4} \right) t g - \left( \frac{\rho_w C_D V^2}{2} \right) \left( \frac{\pi d^2}{4} \right) \quad [1]$$

where  $\rho_i$  and  $\rho_w$  are the densities of ice and water, respectively ( $\text{kg/m}^3$ );  $d$  is the particle diameter (m);  $t$  is the particle thickness (m);  $a$  is the acceleration of the particle ( $\text{m/s}^2$ );  $g$  is the acceleration due to gravity ( $\text{m/s}^2$ );  $C_D$  is the drag coefficient; and  $V$  is the particle rise velocity (m/s). By assuming that the acceleration of the particles was negligible, i.e. that the particles had reached their terminal velocities, Equation [1] was rearranged to give the steady-state rise velocity of a frazil particle as follows,

$$V = \sqrt{2g't/C_D} \quad [2]$$

where  $g'$  is the reduced gravitational acceleration, given by  $g' = g(\rho_w - \rho_i)/\rho_w$ . In order to determine  $C_D$ , Gosink and Osterkamp (1983) developed a best fit curve to data reported by Willmarth et al. (1964) and Schlichting (1968) relating the drag coefficient of a disc to the

Reynolds number,  $Re = Vd/\nu$ , for values of  $Re$  less than 100. This provided the following relationship,

$$\log C_D = 1.386 - 0.892 \log Re + 0.111 (\log Re)^2 \quad [3]$$

Equations [2] and [3] were then solved for different ratios of  $d/t$  and used to plot theoretical rise velocity versus particle diameter curves, and it was found that their data could be enveloped by curves for  $d/t$  ratios of 10 and 50.

Another attempt was made to experimentally measure rise velocities by Wuebben (1984) using a similar procedure to Gosink and Osterkamp (1983), wherein particles were timed as they ascended in a 1 litre graduated cylinder and diameters were estimated. Wuebben (1984) plotted the rise velocity as a function of particle diameter and suggested the following power law relationship,

$$V = 1.9d^{2/3} = 2d^{2/3} \quad [4]$$

where  $V$  and  $d$  are expressed in mm/s and mm, respectively. He noted that because of the scatter in the limited available data, there was no strong justification for selecting any particular relationship; however, the power law had the desirable property of passing through the origin. Wuebben (1984) also fit a similar curve to the data reported by Gosink and Osterkamp (1983), and found the following relationship,

$$V = 4.51d^{0.64} = 4.5d^{2/3} \quad [5]$$

He speculated that the difference between Equations [4] and [5] could be due to differing particle aspect ratios brought on by different nucleation and growth conditions, since Gosink and Osterkamp's (1983) particles were produced in a river, while Wuebben's (1984) were formed in a laboratory environment.

In this study the rise velocity of frazil ice particles was investigated by conducting a series of laboratory experiments. Particles were generated in a frazil ice production tank designed to produce turbulence as the water cools, and images of rising frazil particles were captured in a series of high resolution, cross-polarized digital photographs. This allowed for precise measurement of both the diameter and velocity of each individual particle, and made closer examination of the relationship between rise velocity and particle diameter possible.

## **2. Experimental Setup**

Experiments were carried out in a specially designed frazil ice tank in the University of Alberta Civil Engineering Cold Room Facility. The tank is 0.8 m wide, 1.2 m long and 1.5 m deep

(Figure 1a). The 1.2 m by 1.5 m walls are constructed out of 19 mm thick tempered glass, while the other two walls and bottom of the tank are made of 6 mm thick stainless steel plate. Turbulence is generated in the tank by four plastic propellers powered by NEMA 34 DC variable speed electric motors (1/3 H.P., 13.4 in.-lbs. of torque, max speed 1750 rpm) that are mounted to the tank bottom (Ghobrial et al. 2009). A computer located outside of the cold room was connected to a Sea-Bird SBE 39 Temperature and Pressure Recorder (accuracy  $\pm 0.002^{\circ}\text{C}$  for temperature, 0.05% of full scale range for pressure) enabling real-time monitoring of the water temperature and the degree of supercooling during the experiments.

Lighting for the experiments was provided by two arrays of 24 Larson Electronics 3 watt LED lights that were mounted against the back wall of the tank and diffused by a 1.5 mm thick piece of translucent plastic sheeting. Two Cavisson 4x4" glass linear polarizing filters mounted 22 mm apart, and rotated at 90 degrees with respect to each other, were suspended in the tank flush to the glass wall opposite the lights, such that the centre of the measuring volume was 1.06 m above the bottom of the tank. This cross-polarized the light passing through the filters, which has the effect of producing a black background upon which only ice particles are visible, as they refract the incident light that passes through them. A Nikon D800 digital single-lens reflex (DSLR) camera equipped with a Kenko 25 mm Uniplus Tube DG extension ring and an AF Micro-Nikkor 60 mm f/2.8D lens was used to capture the images. The camera was mounted on a tripod such that the face of the lens, when fully retracted, was 55 mm away from and parallel to the front wall of the tank (Figure 1b). The lens was then focused on a plane approximately half way between the two polarizing filters. Images approximately 4.1 cm wide and 2.7 cm tall with a resolution of 36 megapixels (7360 x 4912 pixels) were captured during each experiment using the following camera settings: ISO 6400, shutter speed 1/2000 s, and aperture of f/25. These settings were found to provide the optimal balance of image clarity and brightness during preliminary experiments.

### **3. Experimental Procedure**

Data was collected during the latter stages of experiments that were carried out to study the size distribution of suspended frazil ice particles. The temperature of the cold room was maintained at  $2^{\circ}\text{C}$  between experiments to allow any ice from the previous experiment to melt. Before the temperature was reduced, the polarizers were mounted in the tank, the propellers switched on, and the thermometer was programmed to record the water temperature every 1.5 seconds for the duration of the experiment. The clocks in the thermometer and camera were synchronized with the computer being used to monitor the temperature in real time, in order to record all data with a common time base. The temperature in the cold room was then reduced to  $-10^{\circ}\text{C}$ .

Next, the camera was programmed to the ISO, shutter speed, and aperture settings described above, taken into the cold room, and set up level on the tripod. This was done five to ten minutes before the water temperature reached  $0^{\circ}\text{C}$ , otherwise frost would form on the lens. The LED lights were powered on, the camera focus was adjusted, and scale images were taken of a

clear plastic ruler situated first at the front and then at the back of the measuring volume. Background images were then captured while there was no ice present in the tank to allow for removal of any imperfections in the glass, spots on the lens, or background light that had passed through the polarizing filters prior to processing.

Once the water temperature reached 0°C, image acquisition for the suspended frazil ice experiments began. A total of 999 images were taken at a frequency of 1 Hz for each experiment, which was the maximum number of images the camera could automatically be set to record. This window of 16 minutes and 39 seconds captured the entire frazil ice production process, from the appearance of the first particles through to particle flocculation and rise.

Once the suspended frazil experiments had finished, the propellers were switched off and the residual turbulence in the water was allowed to dissipate for approximately 2.5 to 3 minutes. The camera was switched from the standard mode used for the suspended frazil experiments to the continuous high-speed shooting mode in order to capture images at a rate of four frames per second. Rising particles were then photographed as they passed between the polarizing filters. A series of 200 images could be recorded at a time before the memory buffer in the camera would fill up, at which point a break of a few seconds was required to back up the images to the SD card. Three to five series of rise velocity images were taken in this manner until the majority of the frazil particles appeared to have reached the surface. The camera was then removed from the cold room and the air temperature was increased to 2°C once again, in order to melt the ice prior to the next experiment.

#### **4. Data Analysis**

The first stage of data analysis was performed using a digital image processing algorithm written in Matlab, similar to the one described by Clark and Doering (2006). This analysis was carried out for each individual image using the following steps: 1) pre-processing, where a raw image was loaded, had an averaged background image subtracted from it, and was converted into high and low threshold binary images; 2) particle detection, where the high threshold binary image was dilated and compared to the low threshold image to determine the area of the particle; and 3) particle analysis and validation, where the area and perimeter of each identified particle was compared to the ideal properties of a fitted ellipse to determine which particles were disc shaped and which were not. A more detailed description of the Matlab algorithm is given by McFarlane et al. (2012). The diameter and the location of the particle centroid, among other properties, were calculated for each disc shaped particle, and a histogram of the particle sizes was generated for the suspended particle images. An example of this can be seen for the suspended particle data obtained during the November 7, 2012 experiment in Figure 2.

The second stage of analysis for the rise velocity images was performed by manually interpreting the particle data calculated by the Matlab algorithm and tracking each rising particle to determine its rise velocity. This was done by identifying the centroid of a particle as it moved from one

image to the next and copying these values into a Microsoft Excel spreadsheet, keeping track of the image number that the particle was first visible in, the time at which the image was taken, and the particle number in that image (particles in an image were numbered from left to right). The particle diameter calculated by the Matlab algorithm was also recorded. Rise velocities for each particle were calculated based on the total displacement in the vertical ( $y$ ) direction, in pixels, between the first and last images in which the particle was visible, and the elapsed time between these images. Through a series of time trials in which continuous high-speed photographs were taken of a digital timer under the same conditions as the rise velocity experiments, it was determined that the camera captured an image once every 0.247 seconds, with a standard deviation of 0.009 seconds. This value of 0.247 seconds was used for calculating the elapsed time. The pixel size was calculated using the scale photographs taken at the front and back of the field of view before each experiment began and ranged from 5.4 to 5.7  $\mu\text{m}$ . In Figures 3a and 3b, 50 superimposed images for the experiments performed on October 23 and November 7, 2012, respectively are presented. The two plots demonstrate the trajectories at which the observed particles were traveling, and the movement of the centroids of tracked particles are marked in red.

## 5. Results and Discussion

The velocities and diameters of the tracked particles ranged from 0.40 to 13.05 mm/s and 0.24 to 2.92 mm, respectively. The rise velocity of each particle is plotted as a function of particle diameter in Figure 4, and it is evident that there is a large amount of scatter in the data. By solving equations [2] and [3] for different aspect ratios it was determined that the data could be enveloped by curves corresponding to  $d/t$  values of 2 and 80 (see Figure 4). Although not much is known about frazil ice thickness, an aspect ratio of 2 seemed highly unrealistic. By comparison, Gosink and Osterkamp (1983) were able to envelope their data with curves for aspect ratios of 10 and 50. The  $d/t = 10$  curve is also shown on Figure 4, and although it can be seen to pass through some of the data for diameters less than 1 mm, it does not provide a good fit to the remainder of the data with larger diameters.

The data points in Figure 4 were further distinguished from each other based on the approximate time that had elapsed since the propellers had been switched off until the first image in which the particle was visible. Looking at the data in this way, it can be seen that all of the particles rising at velocities greater than 5 mm/s corresponded to images taken less than 4 minutes after the propellers had stopped. In Figure 5 the data was plotted with rise velocity as a function of the approximate time since the propellers in the tank had been switched off, and the data points grouped based on the particle diameter. It is clear when looking at Figure 5 that the faster particles were seen earlier, while particles of all sizes were observed throughout the entire range of times. While this could potentially be caused by some residual current in the tank this is unlikely, as it can be seen in Figure 3 that the trajectories at which the particles rose were nearly vertical regardless of how long it had been since the propellers had been switched off.

A more likely scenario is that the faster rising particles had simply risen above the measurement volume after approximately 3 minutes. Considering that the tank is only 1.5 metres deep and the polarizers were mounted such that the centre of the field of view is 1.06 m the bottom of the tank, a particle traveling at a constant velocity of 10 mm/s, for example, would theoretically pass through the field of view after 1 minute and 46 seconds of rise if it had begun ascending from the tank bottom. In reality, it was observed that the particles continued to swirl for a short while after the propellers had been switched off as the turbulent eddies in the tank dissipated, and only then began their ascent. This means that even a fast moving particle starting from the bottom of the tank could take 3 minutes to reach the sample volume. A detailed study of the flow characteristics in the tank after the propellers have been switched off is required to test this hypothesis.

## **6. Conclusions**

The rise velocity of frazil ice particles was investigated by analysing data obtained in four laboratory experiments. Particles were observed with vertical velocities ranging from 0.40 to 13.05 mm/s, and diameters from 0.24 to 2.92 mm. Theoretical solutions for the rise velocity of horizontal discs with varying diameter to thickness ratios were compared to the data, and it was found that the data could be enveloped by curves corresponding to ratios of 2 and 80. Faster particles were observed earlier in the experiments, and while this could have resulted from residual currents in the tank, the vertical direction in which the particles travelled indicate this is likely not the case.

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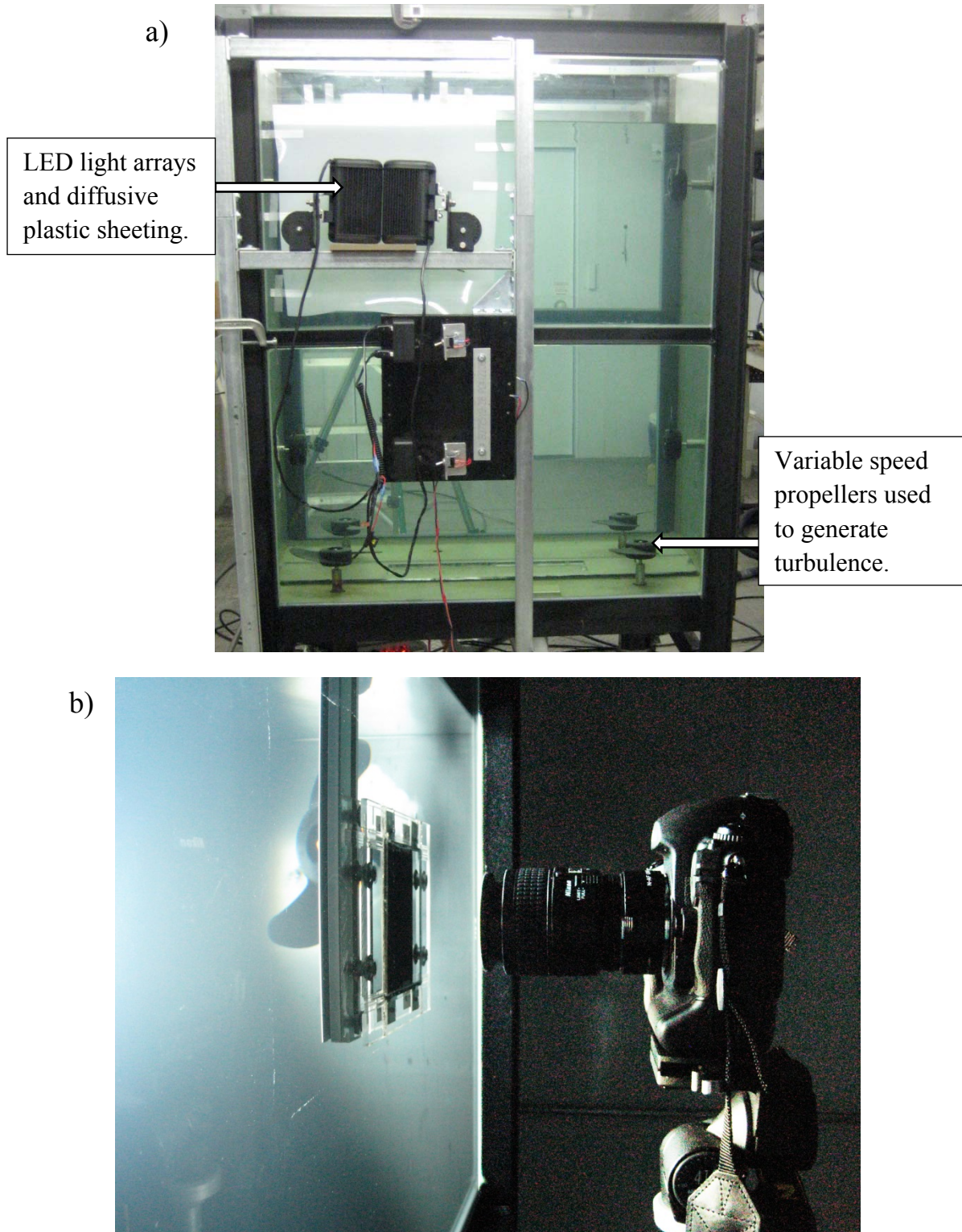


Figure 1. a) Rear view of the frazil ice production tank, and b) the camera mounted with the lens 55 mm from the glass. The two polarizing filters are seen inside the tank.

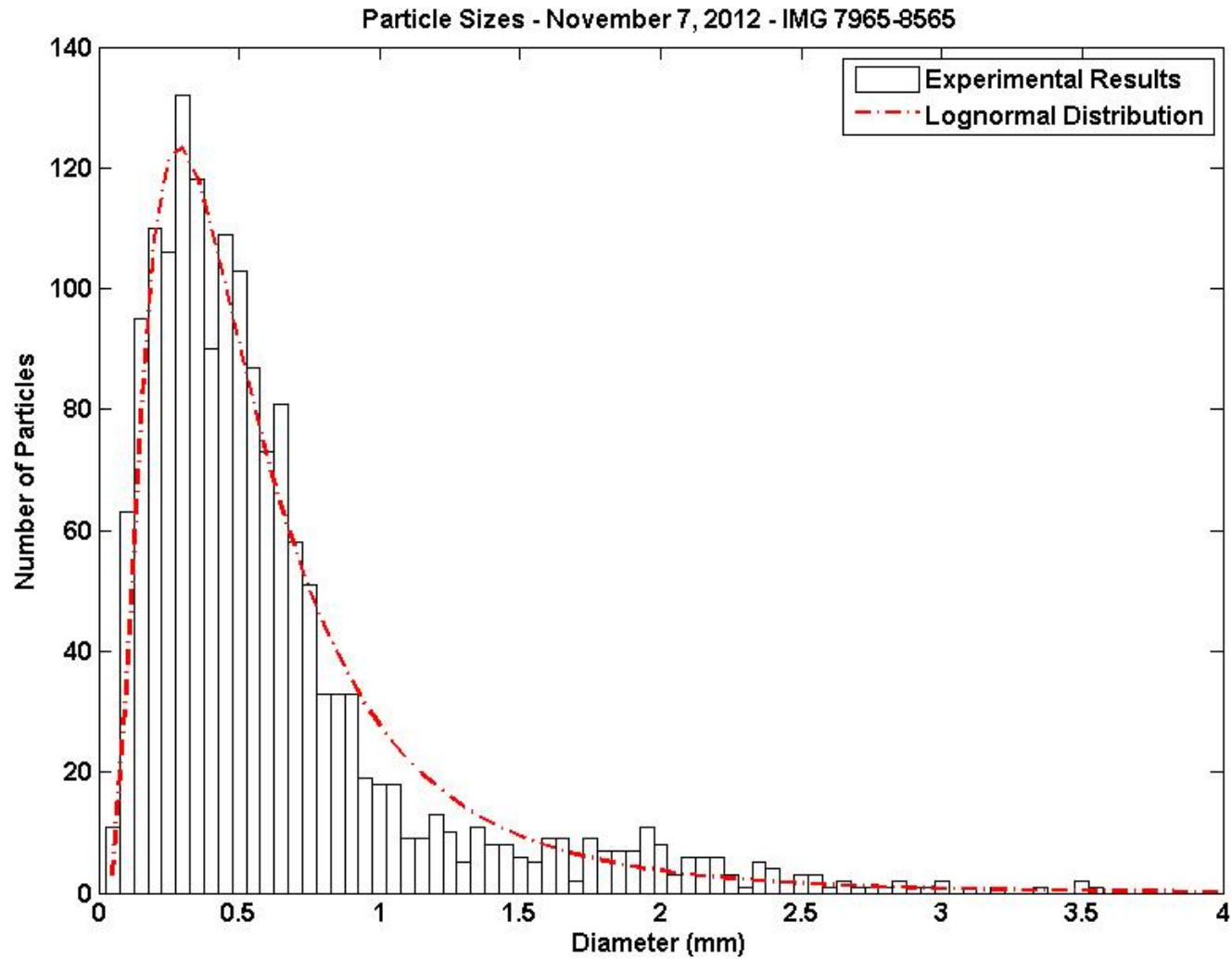


Figure 2. A histogram of the size distribution of suspended frazil ice particles observed prior to particle flocculation on November 7, 2012, fit with a lognormal distribution. The data shown has a mean particle diameter of 0.62 mm and a standard deviation of 0.54 mm.



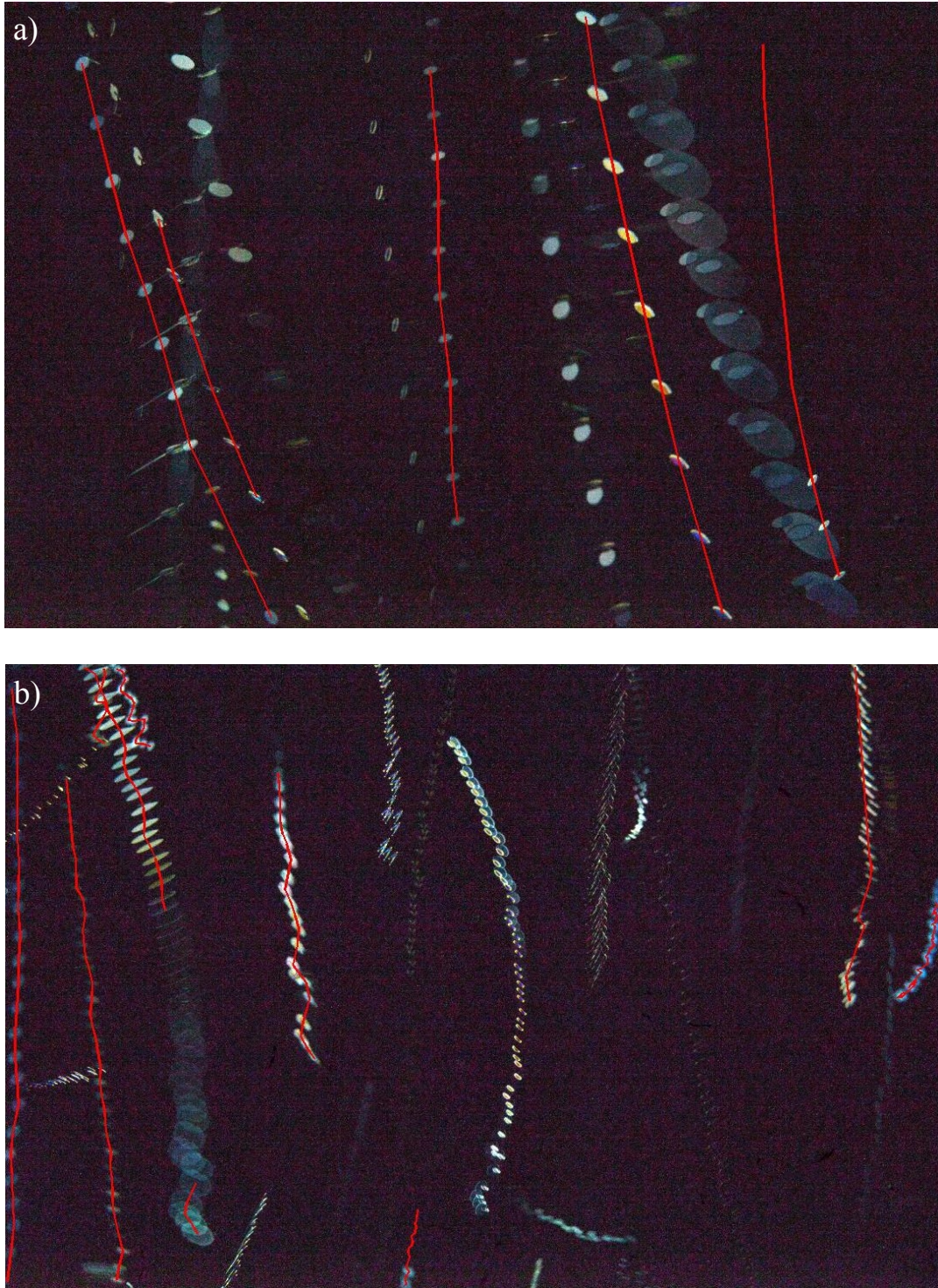


Figure 3. Two time-lapse digital images, each consisting of 50 superimposed rise velocity images for the experiments carried out on a) October 23, 2012, approximately 2.5 minutes after the propellers had been switched off, and b) November 7, 2012, approximately 5 minutes after the propellers had been switched off. The red lines show the path of the centroid of a tracked particle.

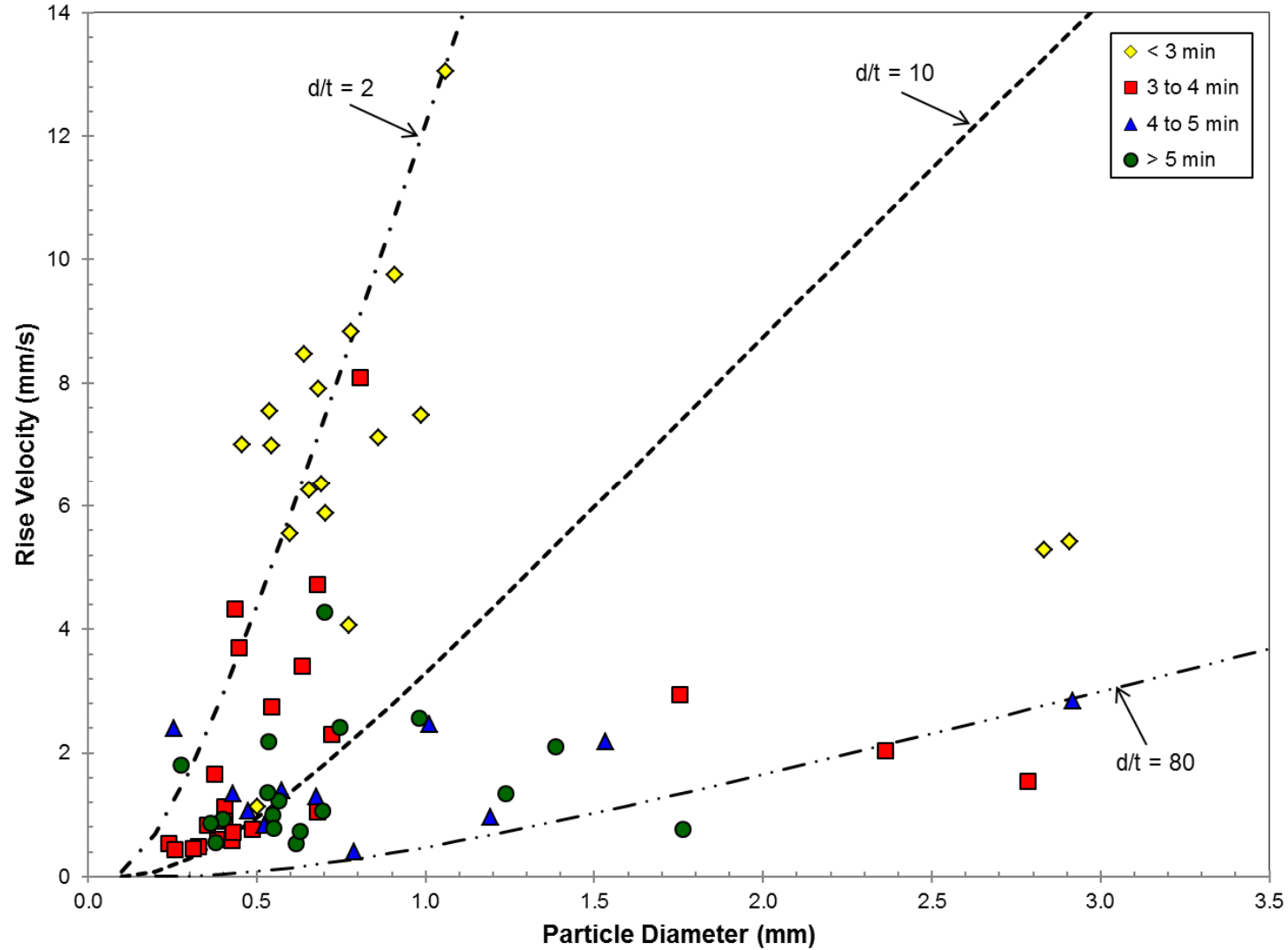


Figure 4. Rise velocity of frazil ice particles plotted as a function of particle diameter. Data points have been distinguished from each other based on the elapsed time since the propellers had been switched off, and theoretical solutions to equations [2] and [3] for aspect ratios of 2, 10, and 80 are shown.

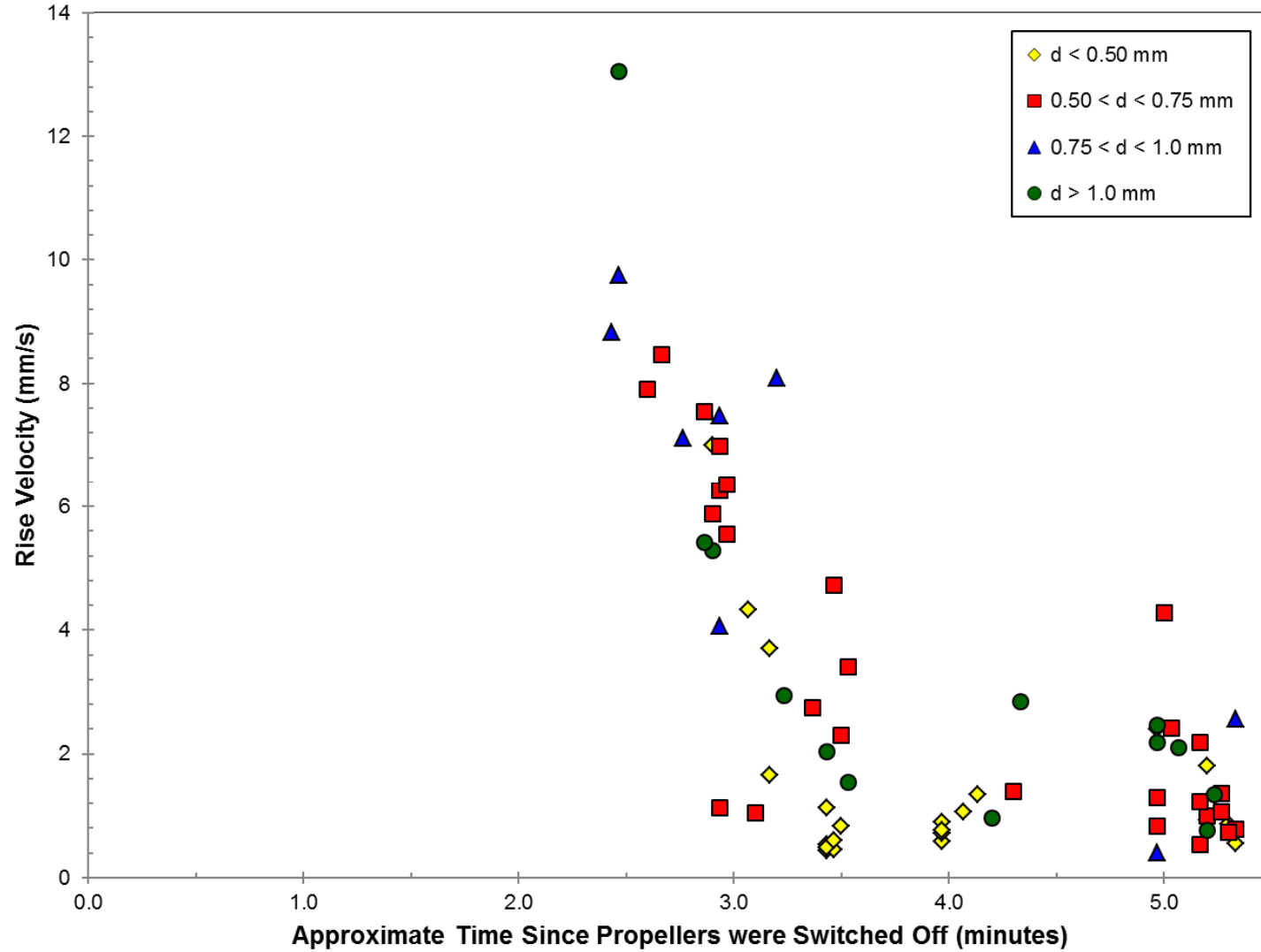


Figure 5. Rise velocity plotted as a function of the approximate time since the propellers had been switched off. Data points are distinguished from each other based on the particle diameter.