Laboratory Studies of Anchor Ice Growth Using A Digital Image Processing System

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A digital image processing system (DIPS) was developed to characterize the properties of frazil ice growth in a series of experiments that were performed using the counter-rotating flume located at the University of Manitoba. The DIPS captured and digitally recorded images of frazil ice as it evolved in the flume. The images were then processed to obtain the number, size, and spatial distribution of the frazil ice particles as a function of time over the duration of an experiment.

1. Introduction

As winter approaches and the air temperature drops, river water will approach its freezing point. If a further drop in water temperature occurs in sufficiently turbulent water, the water becomes supercooled and frazil ice will begin to form. The formation of frazil and anchor ice can adversely affect the operation of a hydroelectric station in many ways. Frazil ice can adhere to the trash racks that protect the intake of a hydraulic turbine, reducing or completely blocking the flow through the unit. This reduction in flow will reduce the potential revenue that can be generated from the unit. Frazil ice can also attach to the riverbed and form anchor ice that changes the geometric and hydraulic properties of the flow. If anchor ice forms downstream of a hydroelectric station, it can increase the staging in the tailrace, which results in a reduction of the net operating head of the generating station and a reduction in the potential revenue.

Our understanding of the hydraulics of frazil and anchor ice formation is very limited (Shen, 1996). Yet the ability to predict the effect that a parameter will have on the formation of ice is essential to the efficient operation of hydraulic structures in cold regions. Some of the parameters of interest include the river velocity, air temperature, bed heat flux, and flow depth. Frazil ice growth has been studied in both the field (Yamazaki et al., 1996) and the lab (Michel, 1963, Carstens, 1966; Hanley and Michel, 1977; Tsang and Hanley, 1985). We know from field observations that these factors influence ice growth, but the quantification of these effects has not yet been achieved.

The research described in this paper was initiated to investigate anchor ice problems occurring on the Lower Nelson River at Sundance Rapids, which are located approximately 4 km downstream from the Limestone Generating Station. During winter operation, anchor ice formation has created an ice bridge that spans most of the channel width, leaving only three or four open-water sections. This ice dam increases tailrace staging by as much as 1.5 m, and reduces the operating head and potential generation revenue. In an effort to alleviate this problem and increase understanding of frazil and anchor ice processes, Manitoba Hydro has sponsored this research.

The purpose of this paper is to:

a) describe a unique research facility used to study frazil and anchor ice;
b) describe the development of a digital image processing system used to examine and characterize the growth of frazil ice; and
c) outline a series of experiments undertaken in a counter-rotating flume to investigate the growth of frazil ice.

2. Research Facility

There are advantages to studying frazil and anchor ice growth from a Lagrangian frame of reference, and one way to accomplish this is to use a counter-rotating flume. A counter-rotating flume provides an “infinite" reach and avoids having to shear actively growing frazil flocs in a recirculating pump-based system. Figure 1 shows the counter-rotating flume, located in the University of Manitoba, Hydraulics Research & Testing Facility (HRTF), that was used for this research. It consists of an inner cylinder within an outer drum that is supported on a turntable. The "bottom" of the flume has separate supports, allowing it to rotate independently of the inner and outer walls. The flume is 0.2 m wide, has a centerline diameter of 1.20 m, and a depth of 0.35 m. The "bottom" of the flume is fitted with removable plates so that the roughness length scale may be readily changed.

The use of a circular flume to simulate a straight channel produces some second-order effects. The centripetal force associated with a rotating column of water induces a pressure gradient and yields an uneven distribution of ice flocs. To counteract these effects, the walls of the flume and the bottom counter-rotate. The relative rates of rotation are set such that the shear stress exerted by the walls offsets the shear stress from the bottom. The result is a stationary mass of water in an absolute frame of reference and the "elimination" of the centripetal force induced by rotation.

The flume is located inside a cold room allowing the heat loss/gain from the water to be controlled by the thermal difference between the air and water temperature. To simulate the geothermal flux from the earth to the water (and also to prevent ice build up on the walls of the flume) the temperatures of the inner, outer, and bottom cavities can be set using an array of PID-based heaters. An array of RTD sensors, with a resolution of 0.002°C, monitors and records the temperature in the flume cavities as well as the heat flux through the bottom plates.

The flume is equipped with two cameras (shown in Figure 2) that are mounted in a cavity built into the outer wall. The first camera is a Sentech STC-1100 B&W progressive scan camera with a 1/3 inch interline CCD. It is positioned such that it captures the entire depth of the water column with a field of view of 10 cm by 8 cm. The images captured from this camera are used in the image processing system. The second camera, a Panasonic CCTV camera, captures a wide-angle view of the flume. The images from this camera are recorded on a time-lapse VCR for reference.

The camera used in the image processing system, captures frazil formation under cross-polarized light conditions (Figure 3). Located inside the inner cylinder, opposite the cameras, are a light source and a polarizing sheet (polarizer 1, Figure 3). The camera lens is also fitted with a polarizer (polarizer 2, Figure 3) that is oriented such that the optic sills are perpendicular to the optic sills on the polarizing sheet; this creates a cross-polarizing condition. The polarizing sheet filters light oscillations perpendicular to its optic sills, while the polarized lens filters light in the other principal direction, preventing any light from directly entering the camera. When frazil ice is backlit from the polarized sheet, the orientation of the polarized light is changed allowing the normally transparent ice to be seen distinctly by the camera.

3. Digital Image Processing System

The analysis of data collected from the counter-rotating flume is performed using a digital image processing system (DIPS) developed at the University of Manitoba. The DIPS consists of two parts, image collection and image analysis. The collection of the frazil ice images is accomplished with the use of a DIPIX FPG-44 Power Grabber board. The camera transmits an analog signal to the grabber board where the signal is converted to a digital image consisting of 640x480 pixels with 256 shades of grey. The maximum image capture rate of the system is 15 frames per second, but it can be readily modified to attain a capture rate of up to 60 frames per second.

The collection of 15 frames per second throughout the entire experiment, which typically runs for 1-3 hours, would result in an enormous amount of data. A two hour experiment, collecting at 15 frames per second continuously, would yield 108 000 images requiring 32.5GB of storage space. To reduce the quantity of information to a manageable size, images are collected at regular intervals. At the start of the experiment, the user enters the grab rate (1-15 frames per second), the number of frames to grab each cycle, and the time between cycles. A typical experiment uses the following protocol: 80 frames grabbed per cycle acquired at a rate of 5 frames per second; this process is repeated every 60 seconds. Figure 4 illustrates an example of the image collection schedule.

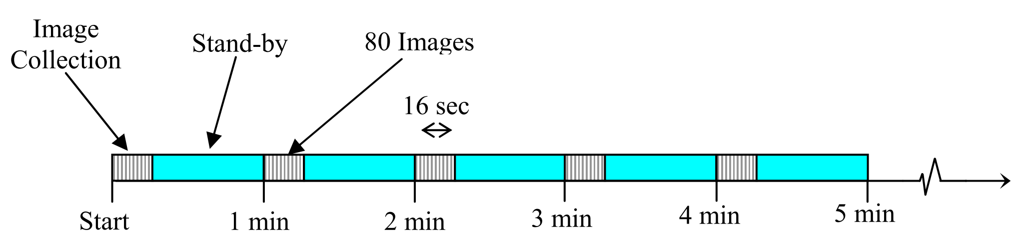

Figure 4. Image Collection Schedule

The analysis of the data begins after the experiment has terminated and all the images have been collected and saved to the computer. Each captured image contains background noise and lighting variations. These disparities affect the edge detection techniques used to isolate the individual frazil ice crystals, and therefore need to be removed. This is accomplished by obtaining a reference image. Fifty images from the start of an experiment, before ice has formed in the water, are averaged together to form one reference image. This image is then subtracted from the images containing frazil ice particles, leaving just the silhouette of the individual ice crystals on a black background. The frazil ice particles on this enhanced image are then counted, sized and their distance from the water surface is recorded.

4. Laboratory Experiments

A series of experiments were recently conducted at the University of Manitoba and analyzed using the image processing system described previously. Table 1 shows two experimental runs and the variables associated with each run.

Table 1

Run	V [cm/s]	R_e	F_r	T_{air} [°C]	dT/dt °C/min
Exp8	50	41667	.412	-10	.00545
Exp10	70	58333	.577	-10	.00522

5. Data Analysis

Figure 5 (a) and (b) show the variation of water temperature and the number of frazil ice particles (in the field of view, previously defined) as a function of time. The temperature trace shows that the water becomes supercooled (-0.088°C for EXP8 and –0.06°C for EXP10) after which frazil ice particles are detected. Secondary nucleation of these particles then leads to a rapid proliferation of frazil ice that is associated with a commensurate increase in the water temperature as a result of the release of the latent heat of fusion. When equilibrium is attained (i.e., supercooling ends), the number of frazil ice particles decreases rapidly as a result of flocculation processes.

Figure 6 (a) and (b) show the average projected area of the frazil ice particles superimposed on the water temperature profile. As seen in Figure 5 showing the number of particles, the projected area of the frazil particles also increases rapidly after the maximum supercooling point has been reached. The average projected area of frazil particles also decreases rapidly after equilibrium has been reached.

Figure 7 (a) and (b) shows the frazil particle size distribution for three specific times that correspond to the beginning, maximum, and end of supercooling process. Figure 8 (a) and (b) shows the particle size distribution for two specific particle sizes (5.8 mm^2 and 17.6 mm^2). The peak in this figure corresponds to the peak supercooling period demonstrated in Figures 5 and 6. It appears that when the total number of particles is increasing during the period of supercooling, all particle sizes seem to be increasing in number.

6. Summary

A digital image processing system has been developed at the University of Manitoba, Hydraulics Research & Testing Facility, to characterize the temporal evolution of frazil ice size, density, and spatial distribution. An extensive series of experiments is currently underway to elucidate the relevant parameters and their role in governing the evolution of frazil ice. This is part of a larger, ongoing, research initiative at the University of Manitoba.

Acknowledgements

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Figure 1. The University of Manitoba counter-rotating flume.

Figure 2. Array of CCD cameras used to monitor frazil ice.

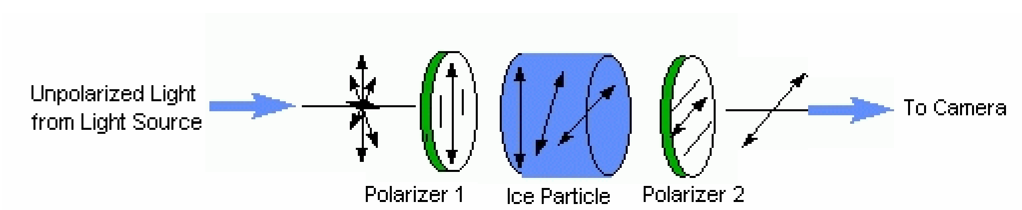
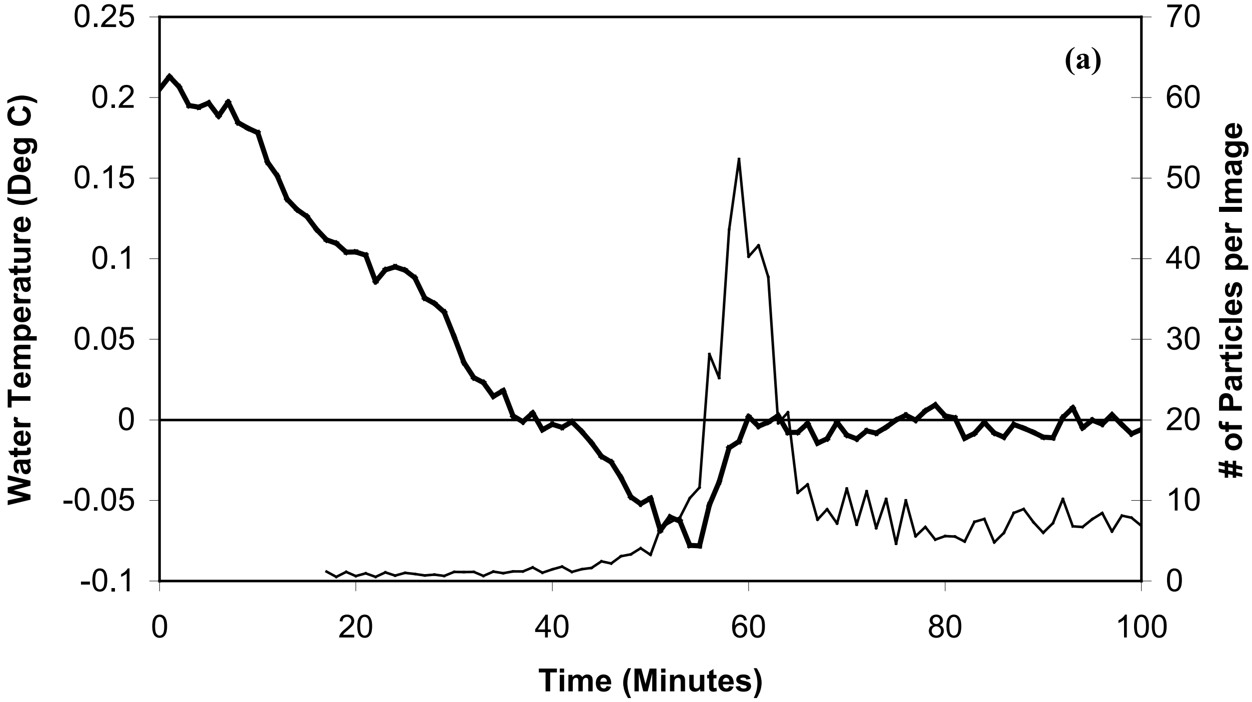


Figure 3. Polarized lighting arrangement used to identify frazil ice.



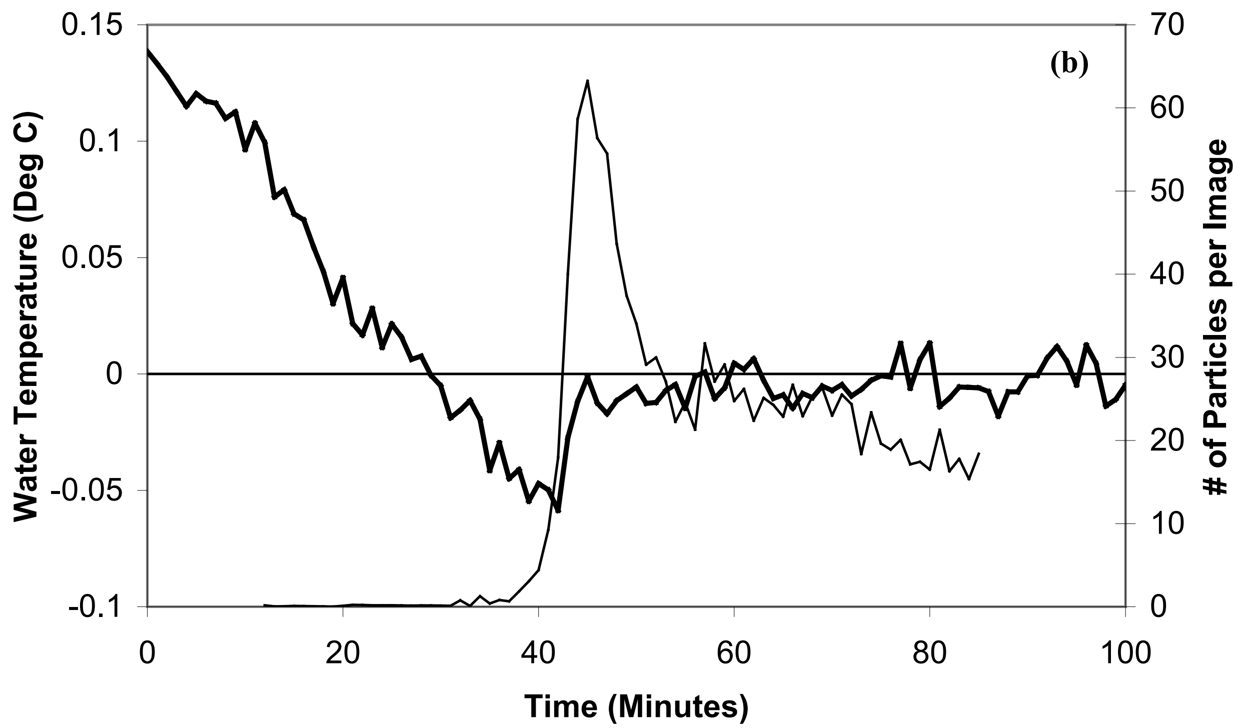


Figure 5. Water temperature and number of particles versus time for **(a)** EXP8 and **(b)** EXP10. Note, ▬ and — denote water temperature and number of ice frazil particles, respectively.

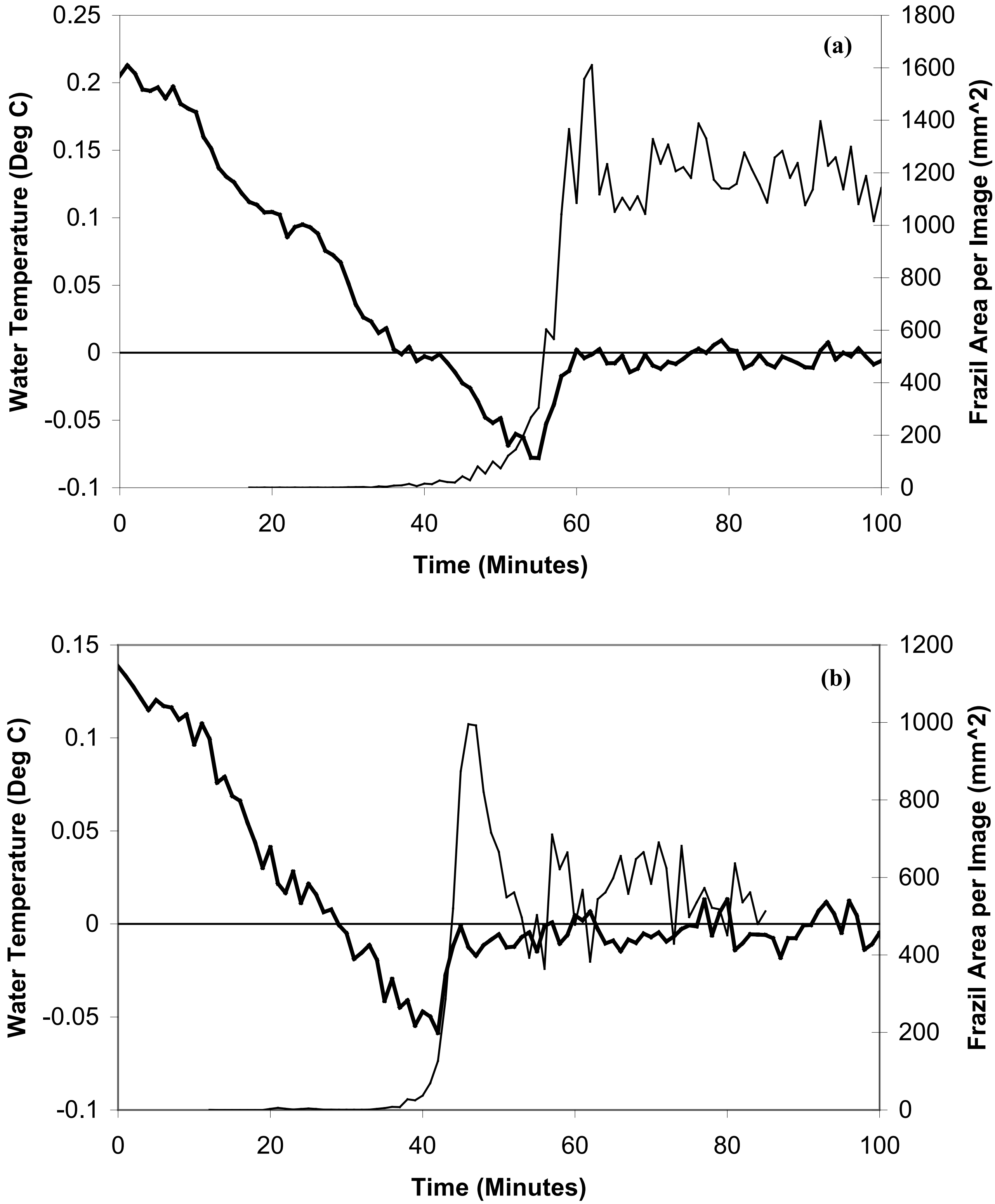


Figure 6. Water temperature and projected area of frazil particles versus time for **(a)** EXP8 and **(b)** EXP10. Note ▬ is water temperature and — is frazil ice area.

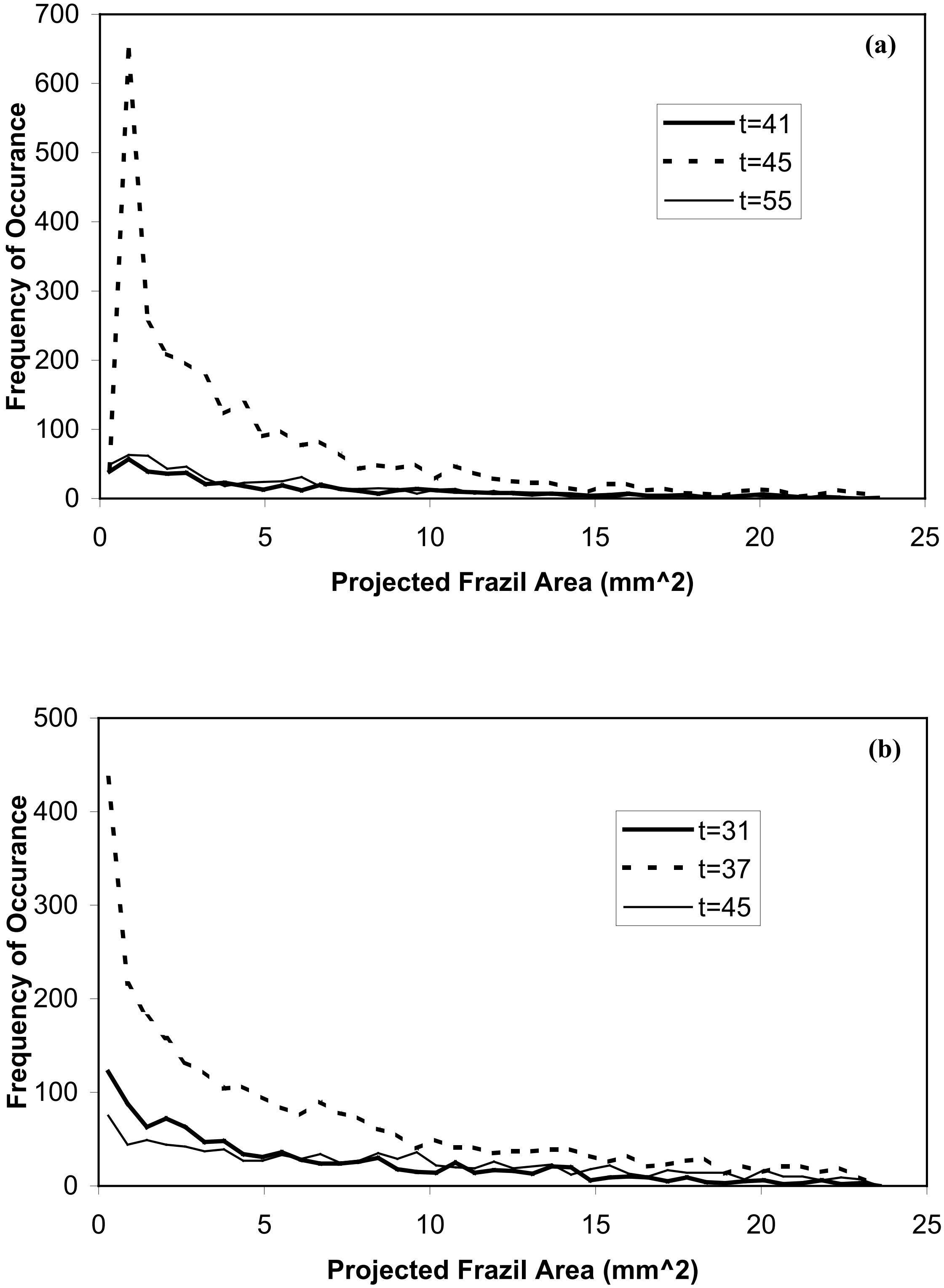


Figure 7. Particle Size Frequency Curve for three specific times **(a)** EXP8 and **(b)** EXP10.

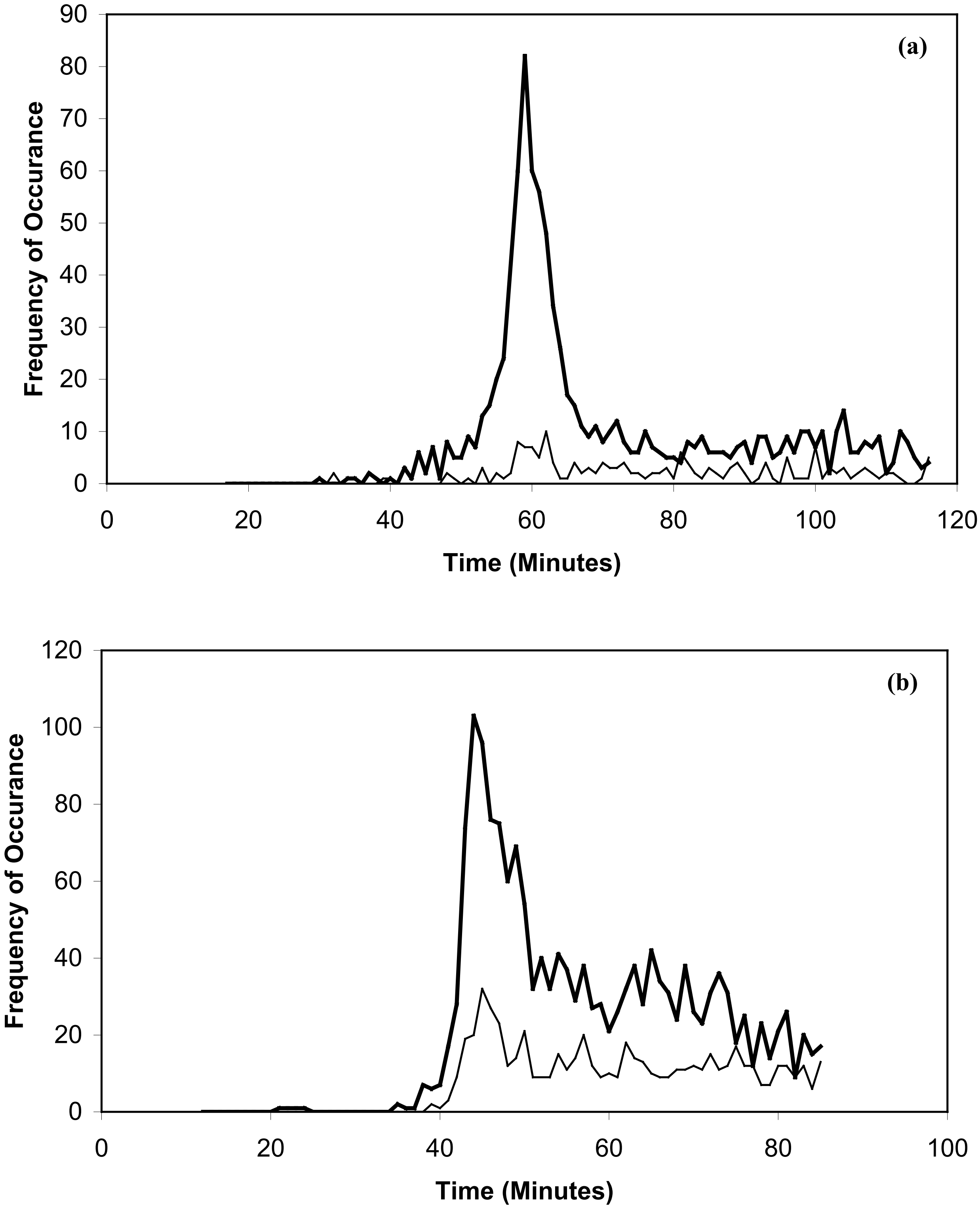


Figure 8. Particle Size Frequency Curve for particle sizes of 5.8 mm^2 (▬) and 17.5 mm^2 (—) for **(a)** EXP8 and **(b)** EXP1