22nd IAHR International Symposium on Ice
Singapore, August 11 to 15, 2014

Effects of Turbulence Intensity on Frazil Ice Particle Characteristics

Vincent McFarlane, Mark Loewen, and Faye Hicks
Department of Civil and Environmental Engineering, University of Alberta
3-036 Markin/CNRL Natural Resources Engineering Facility
Edmonton, Alberta, Canada T6G 2W2
vmcfarla@ualberta.ca; mrloewen@ualberta.ca; faye.hicks@ualberta.ca

Obtaining accurate measurements of frazil ice particles in natural streams is a challenging task and consequently knowledge of the impact of various river characteristics on the development and growth of frazil ice particles is quite limited. One of these characteristics, the turbulence intensity, is highly variable from one location to the next and is believed to have a significant impact on the nucleation rate, growth, and flocculation of frazil crystals. A series of laboratory experiments were performed at three different turbulence intensities to study this hypothesis. Frazil ice particles produced at each of these turbulence intensities were photographed while passing between two cross-polarising filters. The high-resolution images obtained were analysed using a computer algorithm to determine the diameter of each individual frazil particle and the number of particles observed. It was seen that the mean particle diameter decreased linearly with increasing turbulence intensity and was found to range from 0.67 to 0.94 mm. In all cases the particle size distribution was accurately represented by a lognormal distribution.

Proceedings of the 22nd IAHR International Symposium on Ice

ISBN: 978-981-09-0750-1
doi:10.3850/978-981-09-0750-1_1251

1. Introduction

Frazil ice particles form at the beginning of the river freeze-up process, when the turbulent river flow supercools to a temperature slightly below 0°C. Individual frazil ice particles are primarily disc shaped and have been observed to range from approximately 23 µm to 5 mm in diameter in laboratory settings (McFarlane 2014). The size distribution of laboratory frazil particles has been shown to be well described by a lognormal distribution (e.g. Clark and Doering 2006; Daly and Colbeck 1986; McFarlane 2014; Ye et al. 2004). However, the influence of various flow characteristics, such as turbulence intensity, on the development of frazil ice particles is still not well understood.

A few experiments have been performed to study the effects of varying turbulence intensity on frazil particle size. Ettema et al. (1984) used an oscillating grid in a turbulence jar to produce flows with varying turbulence intensities. They did not measure size distributions for their experiments but did note that the maximum observed frazil 'platelet' size decreased with increasing levels of the turbulence exchange coefficient from approximately 6 to 19 cm^2/s. Ye et al. (2004) studied the size distribution of frazil particles at various air temperatures and water velocities in a counter-rotating flume and observed that higher water velocities, corresponding to greater Reynolds numbers, led to the formation of larger frazil ice particles. Clark and Doering (2008) found that the mean diameter of laboratory frazil particles increased with turbulence intensity up to a point corresponding to a turbulent energy dissipation rate of approximately 900 cm^2/s^3, at which point the mean particle size began to decrease. The relationship between mean particle diameter and turbulence intensity was accurately described using a parabolic function.

The results obtained by Clark and Doering (2008) support the theoretical analysis presented by Daly (1984, 1994, 2013) who suggested that the limiting factor in the growth rate of a frazil particle's diameter is the rate at which the latent heat released by crystallisation is advected away from the crystal by the flow. This means that as the turbulence intensity increases frazil crystals would grow more quickly and presumably to a larger crystal diameter. However, high levels of turbulence also lead to increased crystal collisions, both with each other and with hard surfaces such as the river bed and banks. These collisions can cause the frazil particles to break into smaller pieces that will then seed the formation of new crystals, a process known as secondary nucleation. Daly (2013) noted that this results in a relatively large number of small frazil crystals at high turbulence levels.

The purpose of this study was to explore the effects of increasing turbulence intensity on the mean diameter of frazil ice particles. A series of laboratory experiments was performed in a frazil ice tank at various turbulence intensities to achieve this and frazil particle sizes were measured from high-resolution digital images, allowing very small particles to be included in calculating the properties of the particle size distribution.

2. Experimental Setup

Cold room experiments were carried out in a 0.8 m wide by 1.2 m long tank filled with water to a depth of 1.3 m. Turbulence was generated at the bottom of the tank with four variable speed propellers. The water temperature was recorded during the experiments using a Sea-Bird SBE 39 temperature sensor (accuracy ±0.002°C). Lighting for the experiments was provided using two arrays of 24 3-watt LED lights that were mounted flush to the back glass wall of the tank and diffused by a piece of 1.5 mm thick translucent plastic sheeting (Figure 1). Two 10 cm square glass polarising filters were mounted in the tank directly opposite the light source and flush to the front wall, spaced 2.2 cm apart to allow frazil ice particles to pass between them. The filters were oriented at 90 degrees with respect to one another to cross polarise the incident light, producing an image with a black background in which only the ice particles that had refracted the light passing through them were visible. A Nikon D800 digital single-lens reflex (DSLR) camera equipped with a 60 mm macro lens and a 25 mm extension tube was mounted in front of the tank to photograph the frazil particles. Velocity time series measurements in the tank were recorded using a Nortek Vectrino acoustic Doppler velocimeter (ADV). The ADV was mounted on an adjustable metal frame that allowed for velocity measurements at a number of different points in the tank.

3. Experimental Procedure

At the start of each experiment the speed of each of the four propellers located on the bottom of the tank was set to the desired speed (125, 225, or 325 rpm) and checked using a laser tachometer. The thermometer mounted in the tank was then programmed to begin recording the water temperature, and the air temperature in the cold room was reduced from 2°C to -10°C. Images were then captured of a clear plastic ruler located at the front, back, and mid-point of the area between the polarisers to focus the camera and provide a scale for processing the frazil images. When the water temperature reached 0°C the camera was activated to record images at a rate of 1 Hz for the remainder of the experiment. An unprocessed sample image of a frazil floc is shown in Figure 2.

Turbulence intensity was measured while the water temperature was constant at approximately 2°C using the Vectrino ADV. For each of the three propeller speeds ADV measurements were made at nine different depths for three different vertical profiles. The vertical profile locations were at the centre of the tank, along the front glass wall where the polarisers were placed when collecting images, and directly above one of the propellers. These locations were chosen to obtain an understanding of the turbulence characteristics throughout the tank. For the 125 and 225 rpm propeller speeds measurements were taken at a frequency of 50 Hz for five minutes at each location. At the 325 rpm speed a frequency of 100 Hz was used, again for five minutes.

4. Analysis and Discussion

The images were processed using a Matlab algorithm that was designed to identify each individual frazil ice particle and compute its properties. A detailed description of the algorithm is given by McFarlane et al. (2012, 2013). The output of the Matlab algorithm included the diameter of each identified particle and statistics for the entire image series including the mean, median, and standard deviation of the particle diameters observed. In each experiment it was observed that a lognormal distribution provided a good fit to the data; an example size distribution is shown in Figure 3. Using Levene's test for equality of variances (NIST/SEMATECH 2012) the mean particle sizes for each experiment were then compared and it was determined that the experiments could be grouped by propeller speed at a 5% significance level. The mean particle sizes were determined to be 0.94, 0.78, and 0.67 mm for the 125, 225, and 325 rpm experiments, respectively.

The ADV data was analysed using a two-part process. First, the raw ADV data files were de-spiked using WinADV (Wahl 2013) with the algorithm developed by Goring and Nikora (2002) and modified by Wahl (2003). Second, a Matlab algorithm was used to calculate the turbulent kinetic energy (TKE) of the flow using the de-spiked velocity data as the input. At each of the three stations in the tank where the ADV measurements were made, depth averaged values of the TKE were then calculated. Only data that had less than ten percent spikes (i.e. greater than 90% 'good' data) were included when calculating the depth averaged values. The three depth averaged values were then averaged together at each propeller speed to determine a representative TKE value for the flow, which was found to be 22.2, 58.1, and 122.4 cm^2/s^2 for propeller speeds of 125, 225, and 325 rpm, respectively. In Figure 4 the depth averaged TKE at each location and the tank averaged value are plotted for each propeller speed. The mean particle diameter was then plotted versus the propeller speed (Figure 5a) and versus the tank averaged TKE (Figure 5b).

It can be seen in Figure 5 that the mean particle size decreased linearly with increasing propeller speed and TKE (R^2 values of 0.99 and 0.94, respectively). This is in agreement with the findings of Ettema et al. (1984) but contrary to the conclusion of Ye et al. (2004) and Clark and Doering (2008), who both observed an increase in mean particle diameter with increasing levels of turbulence. This discrepancy could be the result of several factors, one of which could be the method by which turbulence was generated in the tank. It is possible that the propellers used in this study and the oscillating grid used by Ettema et al. (1984) to generate turbulence caused large frazil ice particles to fracture as they passed by or collided with the propellers or grid. This fracturing would lead to smaller frazil particles as well as increased secondary nucleation, both of which could reduce the mean particle size. The rough bed plates and counter-rotating flume used to generate turbulent flow by Clark and Doering (2008) and Ye et al. (2004) would likely not lead to as much particle fracturing. Another factor that might explain the discrepancy is the 0.25 to 0.30 mm/pixel resolution of the camera used by Ye et al. (2004); as a consequence they were unable to measure any particles smaller than ~1.25 mm in diameter, thereby increasing the mean of the resulting particle size distribution. Similarly, with a resolution of about 0.056 mm/pixel, Clark and Doering (2008) could only measure particles as small as ~0.2 mm and acknowledged the need to observe smaller particles. The image resolution could also have made it more difficult to distinguish between a small floc composed of only two or three discs and a very large particle. In the experiments being presented, the resolution varied from about 0.005 to 0.006 mm/pixel, and the smallest particles identified were 0.023 mm in diameter. In order to allow for a more direct comparison to Clark and Doering's (2008) data the rate of dissipation of TKE should be computed at the three propeller speeds, and it may be useful to collect more data at even lower turbulence levels to see if there is indeed a vertex in the relationship between mean particle size and turbulence intensity.

5. Conclusions

A series of experiments was conducted in which frazil ice particles were generated at different turbulence intensities and photographed under cross-polarised light in a laboratory frazil ice tank. At each of the propeller speeds used to generate turbulence in the tank, acoustic Doppler velocimeter (ADV) measurements of the turbulence intensity were made at 27 different points in the tank and averaged to determine a representative estimate of the TKE in the tank. The mean particle sizes were 0.94, 0.78, and 0.67 mm and the corresponding values of TKE were 22.2, 58.1, and 122.4 cm^2/s^2, at propeller speeds of 125, 225, and 325 rpm, respectively. The mean particle size was found to decrease linearly as a function of increasing TKE with $R^2 = 0.94$.

Acknowledgments
The authors gratefully acknowledge the support of this research by the Natural Sciences and Engineering Research Council of Canada. The authors would also like to thank Dr. Derek Martin and Christine Hereygers for facilitating access to the cold room facility, and Perry Fedun and Chris Krath for providing technical support and assistance.

References

Clark, S., and Doering, J. (2006). “Laboratory Experiments on Frazil-Size Characteristics in a Counterrotating Flume.” *Journal of Hydraulic Engineering*, American Society of Civil Engineers, 132(1), 94–101.

Clark, S., and Doering, J. (2008). “Experimental investigation of the effects of turbulence intensity on frazil ice characteristics.” *Canadian Journal of Civil Engineering*, 35(1), 67–79.

Daly, S. F. (1984). *Frazil ice dynamics*. Hanover, N. H., 56.

Daly, S. F. (1994). *Report on frazil ice*. Cold Regions Research & Engineering Laboratory, Hanover, N. H., 50 pages.

Daly, S. F. (2013). “Frazil Ice.” *River Ice Formation*, S. Beltaos, ed., Committee on River Ice Processes and the Environment, CGU-HS, Edmonton, Alberta, 107–134.

Daly, S. F., and Colbeck, S. C. (1986). “Frazil ice measurements in CRREL’s flume facility.” *Proceedings of the IAHR Ice Symposium 1986*, International Association for Hydraulic Research, Iowa City, Iowa, USA, 427–438.

Ettema, R., Karim, M. F., and Kennedy, J. F. (1984). “Laboratory experiments on frazil ice growth in supercooled water.” *Cold Regions Science and Technology*, 10(1), 43–58.

Goring, D. G., and Nikora, V. I. (2002). “Despiking Acoustic Doppler Velocimeter Data.” *Journal of Hydraulic Engineering*, 128(1), 117–126.

McFarlane, V. J. (2014). “Laboratory Studies of Suspended Frazil Ice Particles.” University of Alberta.

McFarlane, V., Loewen, M., and Hicks, F. (2012). “Laboratory Experiments to Determine Frazil Ice Properties.” *Proceedings of the Annual Conference and General Meeting of the CSCE - 2012*, Edmonton, Alberta, 1–10.

McFarlane, V., Loewen, M., and Hicks, F. (2013). “Laboratory Measurements of Frazil Ice Rise Velocity.” *Proceedings of the 17th Workshop on River Ice*, CGU HS Committee on River Ice Processes and the Environment, Edmonton, Alberta, 11–23.

NIST/SEMATECH. (2012). “NIST/SEMATECH e-Handbook of Statistical Methods.” <http://itl.nist.gov/div898/handbook/index.htm> (Apr. 2, 2014).

Wahl, T. L. (2003). “Discussion of ‘“Despiking Acoustic Doppler Velocimeter Data”’ by Derek G. Goring and Vladimir I. Nikora.” *Journal of Hydraulic Engineering*, 129(6), 484–488.

Wahl, T. L. (2013). “WinADV.” U.S. Department of the Interior, Bureau of Reclamation.

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.

Figures

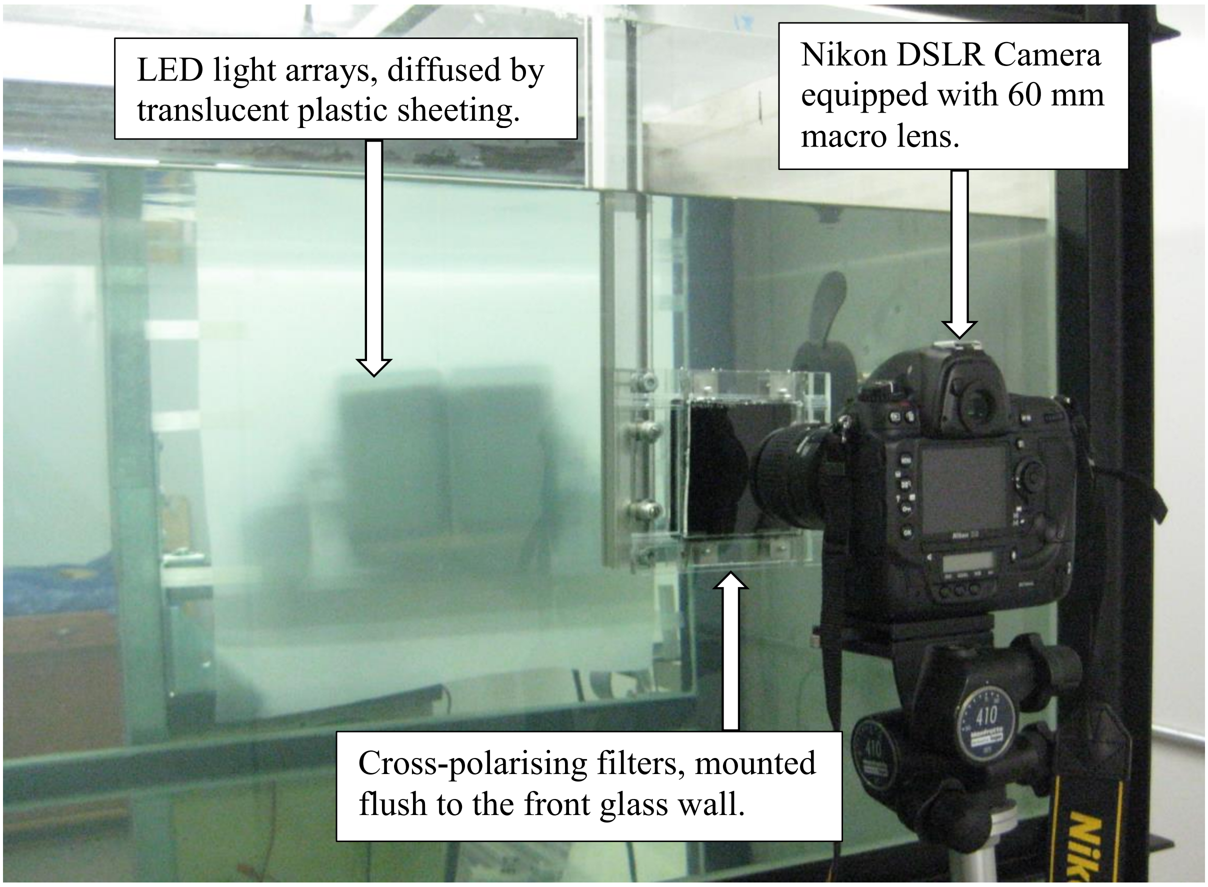

Figure 1. Photo of the camera, polarising filter, and lighting setup in the frazil ice tank.

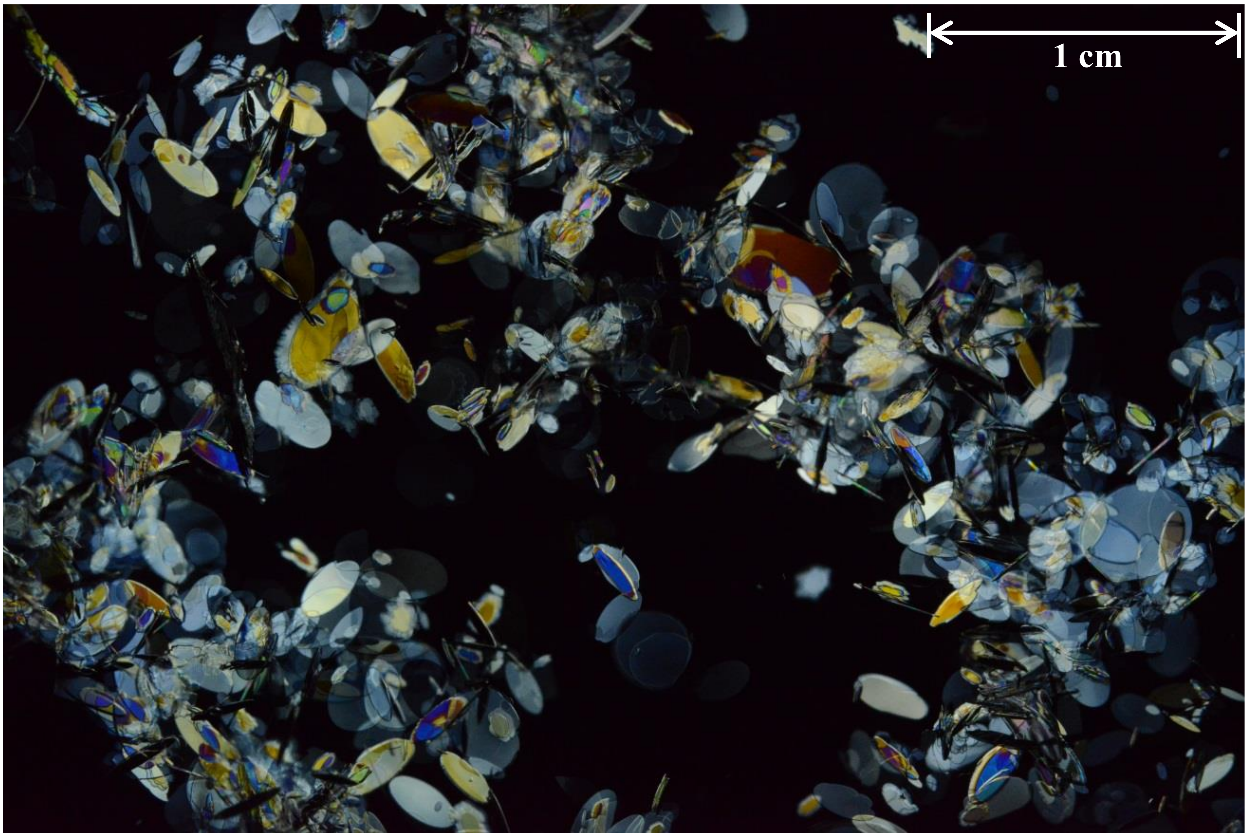

Figure 2. A raw image showing flocculated frazil ice particles.

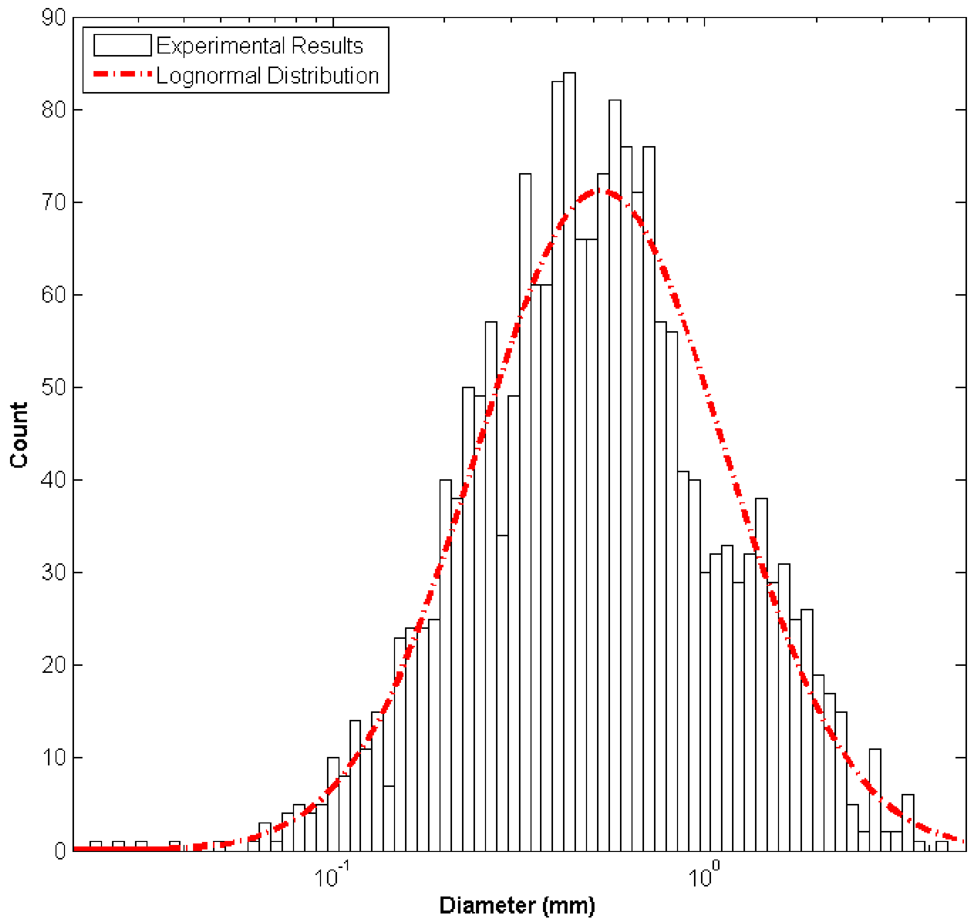

Figure 3. A histogram of particle sizes for a 325 rpm experiment fitted with a lognormal distribution.

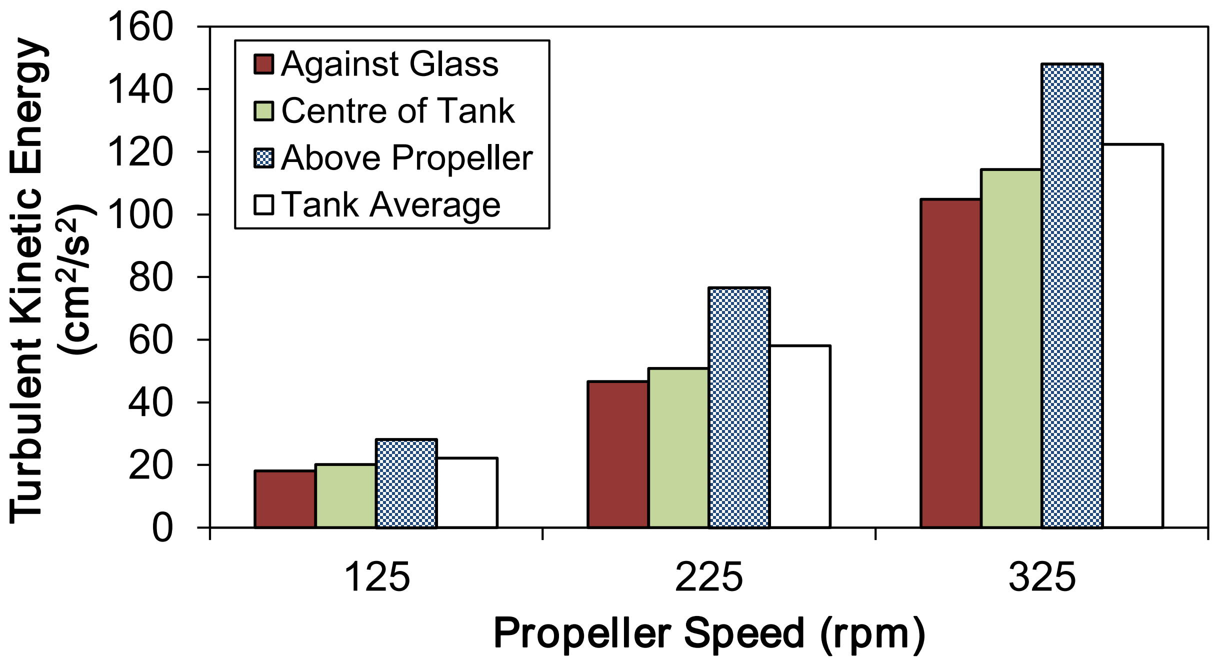

Figure 4. Depth averaged and tank averaged values of turbulent kinetic energy at the three propeller speeds.

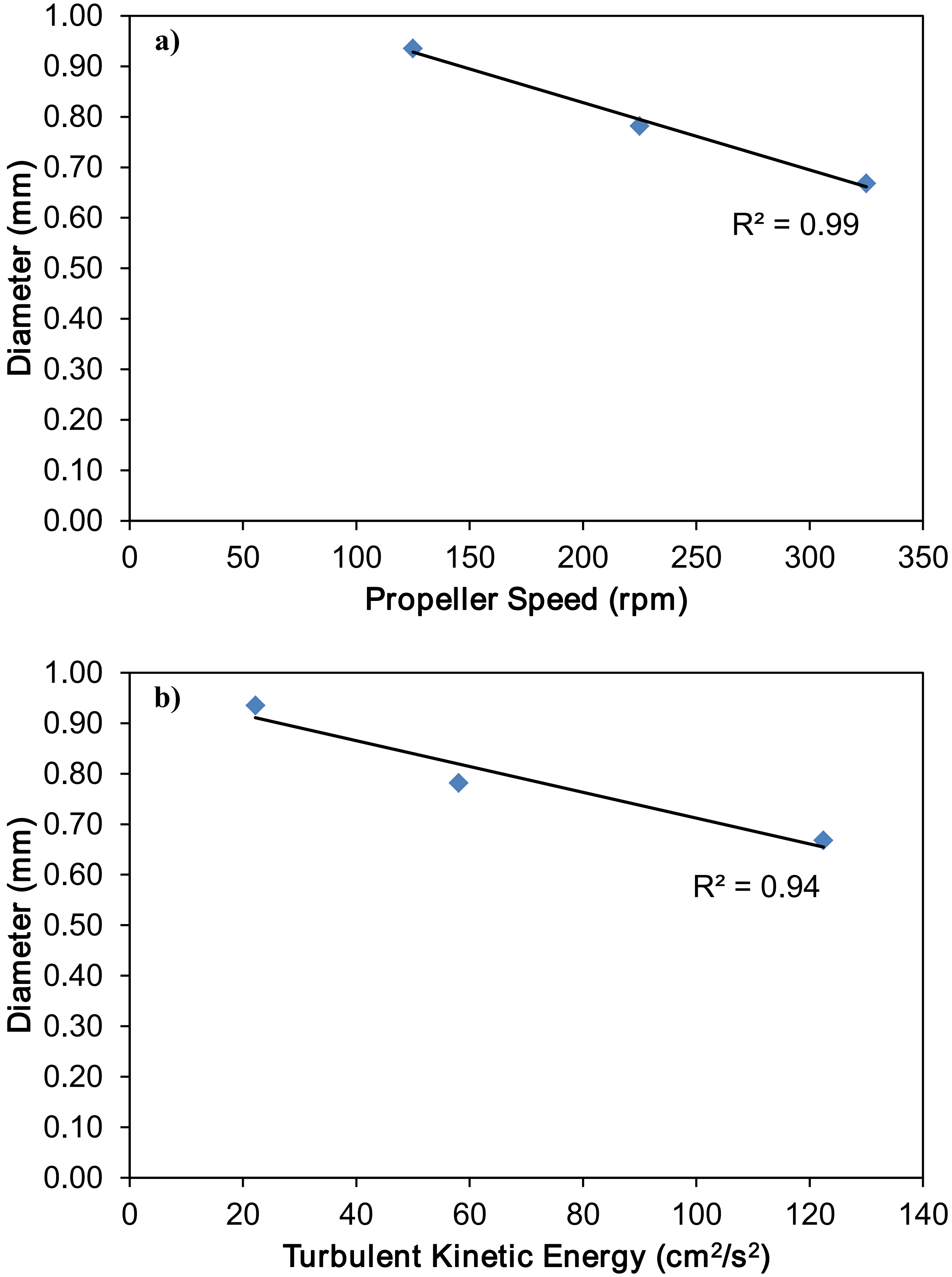

Figure 5. a) Mean particle diameter as a function of propeller speed and b) mean particle diameter as a function of turbulent kinetic energy, both fit with linear regression curves.