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Laboratory measurements of the rise velocity of frazil ice particles

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ABSTRACT

The rise velocity of frazil ice particles has proven difficult to measure with any accuracy. As a result the physics of rising frazil ice particles are poorly understood, making it difficult to determine whether skim ice, frazil ice, or both will be present during the early stages of river freeze-up. Past experimental studies have observed particles rising at a wide range of velocities, but without precise measurements of the particle diameter no definitive relationships could be determined. In this study, high-resolution digital images were taken of rising frazil ice particles as they passed between two cross-polarising filters. An image processing algorithm was used to accurately calculate the diameter of each rising particle and the movement of its centroid was then tracked through a series of images to determine the rise velocity based on the total vertical displacement. Rise velocities ranging from 0.40 to 13.47 mm/s for particles with diameters in the range of 0.24 to 3.35 mm were observed. Existing theoretical solutions for the rise of a horizontal disc were compared to the measured data and a new function relating the rise velocity to the diameter of a vertically oriented rising disc was derived. It was found that all of the data could be enveloped by curves corresponding to a vertical disc with an aspect ratio of 10 and a horizontal disc with an aspect ratio of 80. In some cases, the thickness of a particle could also be estimated from the images and thicknesses ranging from 0.03 to 0.12 mm with a mean of 0.07 mm were observed with aspect ratios in the range of 11 to 71. Based on this information it is suggested that the assumption of discs having a constant aspect ratio is inaccurate.

1. Introduction

Formation of a river ice cover is a complex process influenced by many variables but not all of them are fully understood. It is well known that water will become supercooled near the air-water interface when the air temperature drops below zero prior to freeze-up, leading to the formation of small ice particles on the surface. In calm waters these particles will grow quickly at the surface leading to the formation of a skim ice cover or, if the velocity is high enough, a skim ice run (Clark, 2013). However, if the vertical component of the river turbulence is strong enough to overcome the buoyancy of these surface particles they will become entrained in the flow and the supercooling will extend to greater depths, allowing these particles to seed the growth of frazil ice crystals (Matoušek, 1992). Similarly, these disc shaped frazil particles will only remain entrained in the flow as long as the river turbulence can overcome the frazil rise velocity, and if the individual frazil particles remain entrained and reach high concentrations, they will accumulate together to form slushy frazil ice flocs, which in turn will rise to the surface and become frazil pans and rafts.

In order to predict whether skim ice, frazil ice, or some combination of the two will dominate the early freeze-up stages, it is important to better understand the physics of rising frazil ice particles. Similar to the study of sediment transport, a logical place to start is with the rise velocity of these particles in quiescent water, which has been suggested by Matoušek (1992) to be a key variable in determining whether or not skim ice will form. The focus of this research was to provide such data for individual frazil particles of varying sizes. A specially designed tank located in the University of Alberta's Civil Engineering Cold Room Facility was used to produce frazil ice particles in turbulent, supercooled water, and high-resolution digital images were captured of these particles as they passed between two polarising filters. Using an image processing algorithm each particle was identified and its diameter was determined, and the movement of the particle was then tracked to determine the rise velocity. A detailed description of the laboratory procedure and image processing algorithm is presented, the data is compared to existing theoretical solutions for the rise of frazil ice particles, and a new expression is derived to estimate the rise velocity of vertically oriented discs in quiescent water.

2. Literature review

Measuring the rise velocity of frazil ice particles is challenging and, as a result, few researchers have attempted these types of measurements to date. Gosink and Osterkamp (1983) used a stopwatch to

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time the rise of frazil ice particles that had been scooped out of the Chatanika River in Alaska with a graduated cylinder and found that the rise velocity generally increased with frazil particle diameter. However, particle diameters were only measured to the nearest 0.5 mm (approximately) using the graduations on the cylinder for scale. Gosink and Osterkamp (1983) also noted that their measurements may have been impacted by residual turbulent motions and that acceleration of small discs in the wake of larger discs was occasionally observed. They also included a number of data points, labelled as lab data, in their plot of rise velocity versus particle diameter but did not provide any description of these laboratory experiments. Based on their observations and assuming a simple force balance between the form drag and the buoyant force acting on a horizontal disc (i.e. a disc rising with its major axis perpendicular to the flow), Gosink and Osterkamp (1983) derived the following equation to predict a particle's rise velocity:

$$\rho_i \pi \left(\frac{d^2}{4}\right) ta = (\rho_w - \rho_i) \pi \left(\frac{d^2}{4}\right) tg - \left(\frac{\rho_w C_D V^2}{2}\right)\left(\frac{\pi d^2}{4}\right) \tag{1}$$

where V is the rise velocity (m/s), ρ_i and ρ_w are the densities of ice and water, 920 and 1000 kg/m^3, respectively; d is the frazil particle diameter (m); t is the frazil particle thickness (m); a is the acceleration of the particle (m/s^2); g is the acceleration due to gravity (9.806 m/s^2); and C_D is the drag coefficient. The acceleration of the particles was assumed to be negligible (i.e. that each particle had reached its terminal rise velocity) and Eq. (1) was rearranged to give the steady-state rise velocity of a horizontal disc shaped frazil particle as follows:

$$V = \sqrt{2g't/C_D} \tag{2}$$

where g' is the reduced gravitational acceleration, given by $g' = g(\rho_w - \rho_i) / \rho_w$. In order to estimate C_D, Gosink and Osterkamp (1983) used data reported by Willmarth et al. (1964) and Schlichting (1968) to derive the following empirical equation relating the drag coefficient of a disc to the Reynolds number:

$$\log C_D = 1.386 - 0.892 \log Re + 0.111 (\log Re)^2 \tag{3}$$

where $Re = Vd / \nu$ is the Reynolds number, ν is the kinematic viscosity of water at 0 °C (1.8×10^{-6} m^2/s), and Eq. (3) is valid for $Re < 100$. Eqs. (2) and (3) were then solved for different ratios of d/t, or 'aspect ratios', and used to plot theoretical rise velocity versus particle diameter curves. Gosink and Osterkamp (1983) found that their data was enveloped by curves for aspect ratios of 10 and 50, and ultimately recommended an aspect ratio of about 20 to represent all frazil particles.

Using a procedure similar to that of Gosink and Osterkamp (1983), Wuebben (1984) also attempted to experimentally measure frazil ice rise velocities while working in a laboratory setting. Although he did not describe how the frazil ice particles were produced, Wuebben (1984) did describe how he timed particles with a stopwatch and estimated their diameters to the nearest 0.25 mm through visual comparison to a scale as they ascended in a 1 l graduated cylinder. After plotting the observed rise velocities as a function of particle diameter, Wuebben (1984) suggested the following power law relationship:

$$V = 0.019 d^{2/3} \approx 0.02 d^{2/3}. \tag{4}$$

Wuebben (1984) noted that, aside from Eq. (4) having the desirable property of passing through the origin, there was no strong justification for selecting any particular relationship due to the scatter in the limited data that was available. Wuebben (1984) also fit a similar curve to the data reported by Gosink and Osterkamp (1983), and found the relationship:

$$V = 0.3751 d^{0.64} \approx 0.45 d^{2/3}. \tag{5}$$

He speculated that the difference between Eqs. (4) and (5) could possibly be due to differing particle aspect ratios brought on by different nucleation and growth conditions, since most of Gosink and Osterkamp's (1983) particles were produced in a river, while Wuebben's (1984) experiments were conducted in a laboratory environment. Assuming Stokes flow (i.e. $Re \ll 1$) Wuebben (1984) derived the following theoretical equation for the rise velocity:

$$V = \frac{g'td}{10.2\nu}. \tag{6}$$

However, he noted that because the Reynolds number is typically greater than one for frazil ice particles, Stokes flow is likely not a good assumption. Each of the solutions presented by Gosink and Osterkamp (1983) and Wuebben (1984) along with their rise velocity data is plotted in Fig. 1.

In addition to Eqs. (2) to (6), a number of other equations exist for predicting the rise velocity of frazil ice and they were summarised by Morse and Richard (2009). Shulyakovskii (1960) (as reported by Zakharov et al. (1972)) derived one such relationship taking into account the kinematic viscosity of water as well as the particle diameter, and provided the equation:

$$V = \left(4.006 \times 10^5\right) \nu d^{0.69}. \tag{7}$$

Ashton (1983) assumed that the rising frazil ice particles would fall in the Stokes range (i.e. $Re \ll 1$) and derived the following equation:

$$V = \frac{g' d_e^2}{18 K_r \nu} \tag{8}$$

where d_e is the equivalent diameter of a sphere with the same volume as the frazil disc (m), and K_r is a constant resistance factor, estimated by Hammar and Shen (1991) to be $K_r = 2$.

Daly (1984) considered three different ranges of particle diameters, corresponding to varying levels of turbulence and drag coefficients for a disc rising with its major axis perpendicular to the flow, and derived the following three equations:

$$V = 0.02\left(g'_D \nu^{-1} d^2\right) \quad \text{for } d < 0.0006\,\text{m} \quad \text{(Stokes range)} \tag{9}$$

$$V = 0.0726\left(g'_D{}^{0.715} \nu^{-0.428} d^{1.14}\right) \quad \text{for } 0.0006\,\text{m} < d < 0.0028\,\text{m} \quad \text{(intermediate)} \tag{10}$$

$$V = \frac{1}{2}(g'_D d)^{1/2} \quad \text{for } d \geq 0.0028\,\text{m} \quad \text{(fully turbulent range)} \tag{11}$$

where the reduced gravity, g'_D, is defined as:

$$g'_D = 2\left(\frac{\rho_w - \rho_i}{\rho_w}\right)\left(\frac{gK_v}{\pi}\right) \tag{12}$$

and K_v, the volumetric shape factor, is calculated based on the particle volume, ∀, as follows:

$$K_v = \frac{8\forall}{d^3}. \tag{13}$$

Matoušek (1992) carried out experiments using discs made of polyethylene to approximate frazil ice particles, noting that polyethylene has the same density of ice and should therefore model the behaviour of ice particles accurately. Although Matoušek (1992) did not specify the exact density of the polyethylene he used, it has since been used to approximate ice in other studies (e.g. Healy and Hicks (2007)) where the density of polyethylene is given to be 920 kg/m^3. Matoušek (1992) measured the rise velocities of polyethylene discs with