Cold Regions Science and Technology 151 (2018) 64–74

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Modelling frazil and anchor ice on submerged objects

Lasse Makkonen*, Maria Tikanmäki

VTT Technical Research Centre of Finland, Finland

ARTICLE INFO

Keywords:
Frazil
Frazil ice
Anchor ice
Ice
Nucleation
Supercooling
Water intake

ABSTRACT

Frazil and anchor ice cause blockage of water intakes and icing of other type of submerged objects. In this paper, the physical mechanisms that control these phenomena are discussed and analyzed. Our conclusions are somewhat different from the views presented earlier. 1) Ice crystals in water may originate from microbubbles and turbulence, so that nucleation may occur regardless of an external source 2) The number concentration of ice crystals may not necessarily increase much during an active frazil ice event, 3) The heat transfer from a frazil ice crystal is controlled by its relative rise velocity, not by water turbulence, 4) The collision efficiency of frazil ice crystals on grid components is so small that frazil typically causes no blockage of submerged water intakes, and 5) Blockage is largely caused by ice platelets that grow in-situ on the structural components. We model frazil and anchor ice formation theoretically and find that the uncertainty about the concentration of ice crystals is the main obstacle to accurate modelling. Within these limits, our model results agree well with the available experimental data.

1. Introduction

During cold weather, water may become supercooled. When the water body is well mixed, supercooling may penetrate to a significant depth, in shallow water all the way to the bottom. Supercooling eventually leads to the accumulation of suspended frazil ice crystals or growth of anchor ice, or both. Blockage by icing causes serious problems for turbine intakes of hydroelectric power plants and for consumer water intakes (Ettema et al., 2002). The most serious potential icing problem is with nuclear power plants that take cooling water from a sea, lake or river. Moreover, frazil and anchor ice may cause flooding of a river (Arden and Wigle, 1972). Ice formation and release of ice at the bottom affects sediment transport (Kempema et al., 1993; Tremblay et al., 2013; Kalke et al., 2015, 2017), and bottom fauna (Gaufin, 1959). Supercooling and frazil crystals in water may endanger fish that are cultivated in rivers and coastal areas, since they are unable to escape such conditions (Brown et al., 2011; Radia, 2013). Furthermore, the formation of frazil ice has a significant impact on the oceanography of sea areas close to floating ice shelves (Jenkins and Bombosch, 1995).

Frazil and anchor ice have been studied for over a century (Barnes, 1906; Altberg, 1936), initially inspired by severe ice-related flooding events in rivers. Much of the later research on frazil has been done to alleviate the problem of ice-induced blockage of intakes of water supplies for communities and power plants (Giffen, 1973; Daly and Axelson, 1989; Daly, 1991; Ettema et al., 2002; Daly and Ettema, 2006; Richard and Morse, 2008; Richard, 2011). In spite of these important studies, many aspects of ice accumulation on water intakes, and formation of frazil and anchor ice in general, are still unclear. Formation of frazil ice in a water column and growth of anchor ice on submerged objects may occur simultaneously, and the relative significance of these two processes has drawn detailed scientific attention only recently (Kempema and Ettema, 2013, 2015; Dube et al., 2014; McFarlane et al., 2016).

Most of the experimental research on frazil ice (e.g. Carstens, 1966; Ettema et al., 1984a, 1984b; Andersson and Daly, 1992; Ye et al., 2004; Clark and Doering, 2006; Ghobrial et al., 2012; McFarlane et al., 2014) and anchor ice (Doering et al., 2001; Kerr et al., 2002) has been made in laboratory conditions, but also many field studies have been made (Richard and Morse, 2008; McGuinness et al., 2009; Stickler and Alfredsen, 2009; Richard, 2011; Dube et al., 2014; Richard et al., 2015; McFarlane et al., 2017).

Extensive theoretical research has been done towards understanding and modelling of frazil events. This includes detailed models that predict the degree of supercooling, concentration of frazil, and the size of frazil particles (Schaefer, 1950; Omstedt and Svensson, 1984; Daly, 1984; Svensson and Omstedt, 1994; Ye and Doering, 2004; Wang and Doering, 2007; Richard, 2011; Matsumura and Ohshima, 2015). These models have confirmed the empirical observations that frazil events typically arise suddenly and are intensive. This emphasizes the importance of correctly predicting these events. The existing models necessarily include descriptions and quantifications of many different physical mechanisms regarding e.g. nucleation of ice, coalescence and

---

* Corresponding author at: VTT Technical Research Centre of Finland, Box 1000, Espoo 02044 VTT, Finland.
E-mail address: lasse.makkonen@vtt.fi (L. Makkonen).

https://doi.org/10.1016/j.coldregions.2018.03.001
Received 3 July 2017; Received in revised form 27 February 2018; Accepted 2 March 2018

rise velocity of frazil crystals, and heat transfer from ice crystals to water. Some of these mechanisms are still poorly understood and their quantification is not straightforward.

In this paper, theoretical modelling of frazil and anchor ice is discussed with the purpose of reviewing the uncertain and potentially inappropriate interpretations of the mechanisms assumed in the previous modelling. Our emphasis is in the engineering aspects of the problem, particularly in understanding the mechanisms resulting in blockage of submerged water intakes. Therefore, less attention is paid to frazil in the oceans and to flocculated frazil and grease ice on the surface of water. Our analysis suggests unorthodox views on the physics of frazil and anchor ice. These views are then adopted in numerically modelling frazil and anchor ice.

2. Nucleation

Frazil consists of ice crystals in water. For ice to grow in a water column, the water temperature T must be below the equilibrium freezing temperature of ice T_e, i.e., the water must be supercooled. For fresh water at atmospheric pressure, $T_e = 0\,^\circ$C, but is slightly lower than this at large water depths and in saline water. The supercooling ΔT is defined as

$$\Delta T = T_e - T \tag{1}$$

Initiation of ice crystals in water may happen by two processes, homogeneous and heterogeneous nucleation. Homogeneous nucleation is a process where nuclei for solidification spontaneously appear throughout the volume of a bulk liquid (Matsumoto et al., 2002). Homogeneous nucleation of ice in pure undisturbed water occurs only when the water temperature gets below about −40 °C (Pruppacher and Klett, 1978). Therefore, homogeneous nucleation is not considered relevant to nucleation of ice in natural water bodies, where ice formation always occurs close to 0 °C.

Small particles of foreign materials in water may act as seeds for nucleation. This is called heterogeneous nucleation, which may occur when the water temperature gets below a material-specific critical temperature. In this case, the initial number of growing ice crystals equals the number of active nuclei. As will be discussed below, water temperature in a frazil ice event never gets close to the critical temperature of heterogeneous nucleation of any known material. Hence, heterogeneous nucleation by foreign particles, such as minerals and biological substances, has been ruled out as the fundamental origin of the nucleation of frazil ice. Accordingly, it is assumed that ice crystals that enter the water column from air initiate the nucleation (e.g. Osterkamp, 1977; Hanley, 1978; Martin, 1981; Hammar and Shen, 1995; Daly, 2008). The settlement of ice crystals on water surface can be related to snowfall, blowing snow, sea spray, or crystals that sublimate in the moist air above the water. In laboratory studies, the frazil process may be initiated by seeding ice crystals or by ice crystals originating from the cooling units of the cold room. Since ice crystal deposition from air is relatively slow, it is further assumed that the number of ice crystals in water increases rapidly in turbulent water due to collisions and shattering.

In nature, deposition of ice crystals from air onto a water surface has been measured, and hexagonal ice crystals with a diameter of 60–350 μm and a number concentration of about $6 \cdot 10^4\,\mathrm{m}^{-3}$ (Osterkamp, 1977) have been observed. The smallest possible ice nuclei that initiates the growth of an ice crystal in water is determined by the surface energy between ice and water ($28\,\mathrm{mJ/m}^2$) and its size can be calculated by the Gibbs-Thomson equation (Makkonen, 2002). At a water temperature of −0.1 °C, the smallest possible radius of curvature is 0.8 μm. The initial ice crystals can be assumed spherical (Wang et al., 2015), but when they grow further, they become disk-like (Schaefer, 1950; Colbeck, 1992; McFarlane et al., 2014, 2015). Upon even further growth, they may turn into hexagonal plates with ice dendrites growing from the corners or assume other more irregular shapes (Arakawa, 1954; Colbeck, 1992; Schneck et al., 2017).

The above description of nucleation of ice in water is accepted quite generally, but leaves room for questions. For example, the conventional explanation does not consider the fact that when supercooled water is mechanically disturbed, it will immediately nucleate and start to freeze, even when no ice particles can penetrate the water. This can be observed e.g. by cooling water in a closed bottle in a freezer, and then shaking the bottle.

For demonstration at a temperature closer to that of frazil formation, we made a simple experiment using fresh water in a glass container submerged in a glycol bath and kept at −1 ± 0.1 °C. The temperature in the room was +7 ± 1 °C. At this positive room temperature there could be no ice crystals in the air that might have settled on the water surface. The container was covered with a lid, through which the propeller axis was installed. As expected at this temperature, there were no ice crystals forming when the propeller was in place and rotating slowly. However, nucleation initiated by increasing the rotation rate of the propeller, resulting in numerous ice crystals in the water. The experiment was repeated three times. The nucleation temperature −1 °C in these experiments was lower than in natural cases of frazil, and we could not detect whether the ice was nucleated in the bulk water, at the propeller blade, or on the sides of the container. However, since the temperature was warmer than −1 °C everywhere in our system, the experiment suggests that nucleation of ice in slightly supercooled turbulent water can be caused by turbulence.

Further support of this mechanism comes from the fact that nucleation of ice in water can be initiated by ultrasound when cavitation bubbles are present (Chow et al., 2003; Zhang et al., 2015). Cavitation bubbles and microbubbles of water-soluble gases may form in natural turbulent water (Caupin and Herbet, 2006), and microbubbles can remain in water for several minutes (Turner, 1961). Hence, there are likely always microbubbles present in highly turbulent natural water. The experiments by Chow et al. (2003) suggest that, in addition to the presence of microbubbles, a disturbance in the scale of the bubbles is necessary for the nucleation of ice. They also showed that, upon nucleation, the bubble that initiates nucleation does not disappear, revealing that nucleation is not caused by the collapse of the bubble. Based on these results, a microbubble can initiate ice particles repeatedly. This may be one of several mechanisms, by which the number of ice crystals during a frazil process can escalate. The role of bubbles in nucleation is supported also by a recent study suggesting that nanobubbles, generated upon impact of a supercooled water droplet, serve as additional nucleation sites (Schremb et al., 2017).

We propose that local dissipation of turbulent energy may act as an impulse on a micro- or nanobubble that initiates nucleation in water. In a turbulent flow, large eddies transfer their energy into smaller ones and so forth, so that the turbulent energy eventually dissipates at the smallest scale of the turbulent eddies. The characteristic size x of the smallest eddies can be determined by Kolmogorov's theory of turbulence, and is

$$x = \left(\frac{\upsilon^3}{\varepsilon}\right)^{1/4} \tag{2}$$

where υ is the kinematic viscosity ($1.8 \cdot 10^{-6}\,\mathrm{m}^2\,\mathrm{s}^{-1}$ for water) and ε is the mean rate of dissipation of turbulent energy per unit mass.

In lakes, ε is estimated to be below $10^{-6}\,\mathrm{m}^2\,\mathrm{s}^{-3}$ and in rivers below $0.1\,\mathrm{m}^2\,\mathrm{s}^{-3}$ (Daly and Ettema, 2006). Thus, based on Eq. (2), in natural conditions, x is typically larger than 0.1 mm. According to Kolmogorov's theory, the characteristic frequency at which turbulence is dissipated equals $(\varepsilon/\upsilon)^{½}$. This, using $\varepsilon = 0.1\,\mathrm{m}^2\,\mathrm{s}^{-3}$, provides a frequency of 0.24 kHz, which is less than one tenth of the dissipation rate that has been demonstrated to nucleate bubbles in water (Chow et al., 2003). However, nucleation is a stochastic process and becomes more probable with a longer duration of acoustic emission (Zhang et al., 2015). Therefore, it appears possible that nucleation of ice in slightly