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Review

Sea spray icing phenomena on marine vessels and offshore structures: Review and formulation

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ABSTRACT

Cold ocean regions have many environmental challenges that pose risks to the stability of both marine vessels and structures and to human safety. One major hazard is the marine or sea spray icing phenomenon. Wave-impact sea spray and wind spray are the main sources of incoming water onto marine vessels and offshore structures that can cause hazardous ice accumulation on those structures. Prediction, assessment, and computation of the icing growth rate and the amount of ice accumulation are important but complex. This paper reviews the history and development of predictive models of sea spray icing on marine vessels and offshore structures. Several topics are reviewed in this paper, such as droplet trajectories, flux of seawater spray, liquid water content (LWC), heat balance at the phase interface, and icing models.

1. Introduction

Marine or sea spray icing and atmospheric icing pose considerable hazards, such as risks to the stability of marine vessels and offshore structures and to the safety of the crew during harsh weather operations. Hay (1956) reported the loss of the trawlers "Lorella" and "Roderigo" as a result of sea spray icing in the fishing grounds north of Iceland in January 1955. Blackmore and Lozowski (1994) reported that this accident was actually the beginning of research on the ship icing problems. Shekhtman (1968) reported that 10 Soviet ships in the Bering Sea were destroyed due to instability by the formation of ice in January 1965. Zakrzewski and Lozowski (1989) reported that many vessel losses have occurred due to icing. Several researchers have reported the risks caused by the icing phenomenon (Brown and Mitten, 1988; Jørgensen, 1982; Makkonen, 1989; Nauman and Tyagi, 1985; Ryerson, 2008, 2009, 2011; Schrøder Hansen, 2012). In the 1980s, Jørgensen (1982) reported the risks of superstructure icing due to seawater spray and atmospheric icing because of precipitation on offshore platforms. Ryerson (2011) expressed the hazards of icing, which include: instability and loss of integrity of marine ships and offshore structures, malfunction of the operational equipment and communication antennas, slippery handrails, ladders or decks, unusable lifeboats and fire equipment, and the blocking of air vents. Figs. 1 and 2 show ice accumulation from sea spray icing on a marine vessel and an offshore structure, respectively.

The mitigation of icing risks can increase safety and efficiency for marine operations in the Arctic and other cold regions. Risks created by the offshore icing phenomenon are a function of the kind of icing, and of how each kind affects special regions and functions of platforms. The icing phenomenon is not generally a major problem, but the kinds of ice that can be experienced offshore, where it forms, and its physical characteristics have significant impacts on activities and regions of platforms (Ryerson, 2009). Fig. 3 illustrates where various ice types can be generated to accumulate on an Arctic semi-submersible platform.

The icing phenomenon on marine vessels and offshore structures has two principal causes in the Arctic and other cold regions: atmospheric icing and marine or sea spray icing. The freezing of freshwater is called atmospheric icing, which includes: the precipitation of rain, snow, hail and drizzle, as well as hoar frost, resulting from the deposition of water vapour directly as ice crystals, and rime ice resulting from super-cooled cloud or fog droplets (Ryerson, 2011). Sea spray icing, or marine icing, occurs for two major but distinct reasons: wave-generated spray and wind-generated spray. The first reason for sea spray icing is because of the impingement of waves on marine vessels and structures. Wave-generated spray is generally a large source that is mostly a short and approximately periodic water flux that is created near the bow of vessels and the base of offshore structures (Dehghani-Sanij et al., 2015; Schrøder Hansen, 2012). Wind-generated spray is a rather small source, but it is a constant water flux that is created in the airflow during windy conditions (Dehghani-Sanij et al., 2015; Schrøder Hansen, 2012). Fig. 4 indicates a typical schematic of a sea spray icing event on a marine vessel.

According to past reports by several researchers (Aksyutin, 1979; Brown and Roebber, 1985; Cammaert, 2013; Kato, 2012; Makkonen,

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Fig. 1. View of a cargo vessel in the Port of Québec, Canada (January 2010) that is covered with a very thick layer of ice (http://www.groupocean.com/en/achievements/view/21).

Fig. 2. Sea spray icing on the Ocean Bounty in the winter of 1979–1980 in Lower Cook Inlet (Jones and Andreas, 2009).

Fig. 3. Ice accumulation regions, through ice type, on the Ocean Rig semi-submersible *Eirik Raude* (Paulin, 2008; Ryerson, 2011).

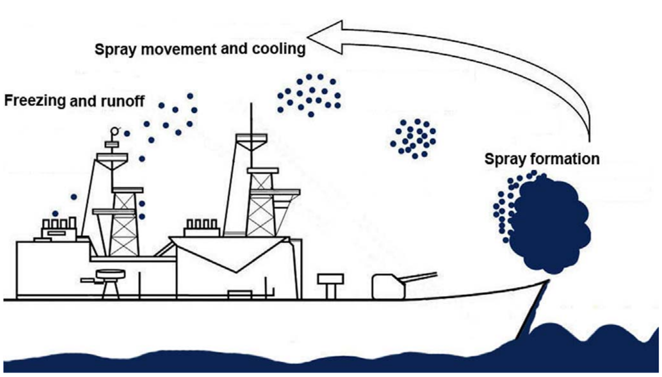

Fig. 4. Schematic of the spray formation and its movement on a ship (Dehghani-Sanij et al., 2015, 2016).

1984a, 1984b; Shekhtman, 1968; Shellard, 1974; Tabata et al., 1963; Zakrzewski, 1986a, 1986b, 1987), sea spray is the main reason for the icing phenomenon in cold regions. Table 1 represents causes of the icing phenomenon based on numerous observations. According to these observations, for all regions, sea spray icing occurs more than 80% of the time of reported icing on marine platforms. Although sea spray icing is not known to be a significant reason for the icing phenomenon in the Arctic, this is likely because of inadequate data.

Some parameters have considerable impacts on the icing phenomenon and ice accretion during a sea spray event. These include: (1) environmental factors such as wind velocity, air temperature, droplets temperature, the freezing temperature of seawater, salinity, the size and distribution of droplets, relative humidity, characteristics of swell waves (height, period, propagation direction), sea or ocean conditions, and (2) the characteristics of marine vessels, including size and design of the vessels, vessel speed, and the angle between the vessel heading and wind/wave direction (Blackmore and Lozowski, 1994; Cammaert, 2013; Guest, 2005; Jørgensen, 1985). In addition, sea spray icing can occur once the following environmental factors exist:

(1) *High wind velocity*. When the wind velocity exceeds approximately 9 m/s, impact-generated spray may impinge on marine platform columns and trusses (Horjen and Vefsnmo, 1985).
(2) *Low air temperature*. According to reports by Tabata et al. (1963) and Tabata (1969), ice accumulation begins at an air temperature of −2 °C, and the highest growth rate of icing intensity occurs at −17 °C, below which the icing rate decreases. Kulyakhtin and Tsarau (2014) reported that the water and its salt content freezes once the brine temperature falls below −23 °C. Furthermore, Lundqvist and Udin (1977) reported that the air temperature must go below −2 °C for icing to occur in ocean water. Cammaert (2013) stated that, for sea spray, ice accumulation occurs when both the air temperature is under the freezing point of seawater (−2 °C), and air-borne brine droplets affect a structure and partially freeze. Some Russian sources reported that once the air temperature is lower than −18 °C, spray icing does not occur; the water droplets will freeze in the air during their flight, convert to ice crystals, and will not adhere to components of marine vessels and offshore structures (Minsk, 1977). However, in reality, there will be many cases of marine icing once the air temperature is below −18 °C (Berenbeim, 1969; Minsk, 1977). Several parameters, such as air temperature, salinity, the size of the droplets, wind velocity, relative humidity, the droplet flight time, and the temperature of the seawater surface have substantial effects on the freezing process of water droplets. Moreover, the size of marine vessels and structures is an important factor.
(3) *Low seawater temperature*. Commonly, sea temperature should be less than 5 °C for sea spray icing (Cammaert, 2013). According to a report by the US Navy (1988), the critical temperatures of seawater for marine icing are between −2.2 and 8.9 °C in the