Ocean Engineering 143 (2017) 1–23

Contents lists available at ScienceDirect

Ocean Engineering

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

Review

Marine icing phenomena on vessels and offshore structures: Prediction and analysis

A.R. Dehghani-Sanij*, S.R. Dehghani, G.F. Naterer, Y.S. Muzychka

Department of Mechanical Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL, Canada A1B 3X5

ARTICLE INFO

Keywords:
Sea spray icing
Marine icing observations
Cold regions
Icing models

ABSTRACT

Past progress in prediction and modeling of ice accumulation on marine vessels and structures located in cold seas and ocean regions is reported and examined in this paper. Research studies have developed models for the estimation of sea spray icing, which is the main reason of marine platforms icing. The phenomenon of sea spray icing is one of the major hazards in cold regions. Hence, prediction, assessment and computation of the icing growth rate and the amount of ice accumulation are important but also challenging. The paper briefly reviews sea spray icing models, along with various experimental, theoretical and numerical approaches. An overall survey shows that outstanding past results were based on field observations and followed by empirical tests. Then, theoretical investigations formulated the experimental results. Also, numerical simulations have led to many predictions of icing phenomena as the supplementary research. In this paper, the sea spray icing models are classified based on when the research was conducted. To obtain more accurate and realistic results from marine icing models, evaluations of the various models have been discussed.

1. Introduction

The population of the world is growing and will likely reach almost 9 billion people by 2048 (Kreith and Krumdieck, 2013). The development of new renewable energy sources is necessary. Energy supply is a basic requirement for the economic and social development of countries. Oil and gas are still among the major sources of energy worldwide. According to a report by Gautier et al. (2009), approximately 30% of the world's undiscovered natural gas resources and almost 13% of the world's undiscovered petroleum resources may be found in the areas north of the Arctic Circle. The resources, which are typically extracted by offshore structures, are generally around 500 m below the water's surface (Gautier et al., 2009). The exploration and exploitation of oil and gas resources in Arctic regions are both technically difficult and costly because there are many environmental challenges, including the freezing of sea spray and atmospheric precipitation. Efimov (2012) reported that after the increase of offshore operations in the cold areas of Norway and Alaska due to the oil exploration and extraction, the icing problems on marine vessels and drilling rigs became a significant important issue and challenge for the oil and gas industry.

Seawater spray and precipitation are the two main sources of icing and ice accumulation in cold seas and ocean regions. Panov (1976) reported that severe ship icing happens mainly in northern regions, such as: the northern coast of Norway and the Kola Peninsula to the Spitsbergen in the Barents sea; in the Northern Atlantic near Canada; in the sea of Okhotsk and in the northern part of the Japan sea; in the Bering sea near shore of Alaska; and near the Kuril Islands and Kamchatka (Efimov, 2012). Table 1 shows the percentage distribution of ship icing among these seas and ocean, which was obtained by Panov (1976) and Vasileva (1971). It should be mentioned that the results obtained by Vasileva (1971) are for the period between 1950 and 1971.

The phenomenon of icing has led to many fishing vessels of small and medium sizes to be lost at sea (Aksyutin, 1979; Fukusako et al., 1989; Guest, 2005; Hay, 1956a, 1956b; Jessup, 1985; Lundqvist and Udin, 1977; Shellard, 1974; Zakrzewski, 1987; Zakrzewski and Lozowski, 1989a) and has adversely affected the stability and movement of small cargo ships (Aksyutin, 1979; Lundqvist and Udin, 1977; Zakrzewski, 1987). According to a report by Hay (1956a), sea spray icing had caused the loss of two trawlers, the "Lorella" and the "Roderigo", in the north coast of Iceland in January 1955. Blackmore and Lozowski (1994) expressed that this accident prompted the start of studies on the ship icing problems. Hay (1956b) and Lackenby (1960) carried out a serious investigation on icing problems involving trawlers. Sutherby (1951) reported that the icing problems of naval ships were fully known after the Second World War. Shellard (1974) provided a list of the loss of 81 vessels from the winter of 1942 to December 1970 due to icing. Fukusako et al. (1989) reported that sea spray icing caused more than 25 severe accidents for fishing vessels from 1960 to 1987 in

* Corresponding author.
E-mail address: adehghani@mun.ca (A.R. Dehghani-Sanij).

http://dx.doi.org/10.1016/j.oceaneng.2017.07.049
Received 19 January 2017; Received in revised form 20 June 2017; Accepted 15 July 2017
0029-8018/

Table 1
Distribution of ship icing among the seas and ocean (Efimov, 2012).

Region	Percentage, obtained by Panov (1976)	Percentage, obtained by Vasileva (1971)
Barents and Norwegian Sea	34.5	38.6
Bering Sea	25.5	25.2
Sea of Okhotsk	18.0	19.3
Western Pacific Ocean	10.5	8
Sea of Japan	8.1	6.2
Baltic Sea	2.4	1.9
Black and Azov Seas	1.0	0.8[a]

[a] This percentage is only for the Black Sea.

Fig. 1. View of ice accumulation on deck of a marine vessel (Cammaert, 2013).

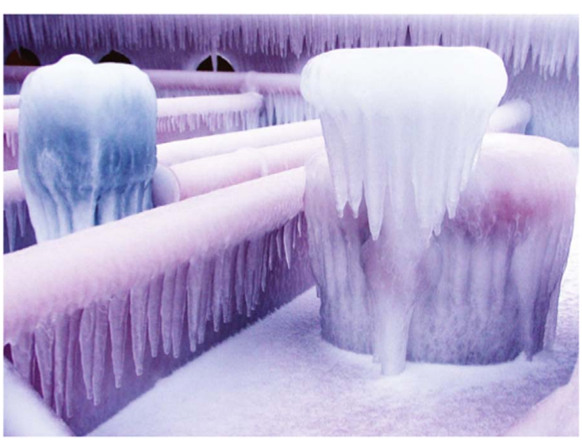

Fig. 2. View of ice formation on a marine structure (Marine Log Website).

the northern winter sea near Hokkaido, Japan. According to a report by Shekhtman (1968), 10 Soviet ships were damaged in the Bering Sea in January 1965 because of instability caused by the accretion of ice. Fig. 1 illustrates an example of ice accretion due to sea spray icing on a marine vessel. Visual and thermal photos can be used to estimate ice loads on structures (Fazelpour et al., 2016a, 2016b). Fig. 2 shows accumulated ice on a marine structure in cold weather conditions.

The main purpose of this paper is to briefly review the sea spray icing models. The icing phenomena including sea spray and atmospheric icing, which are generated due to different sources of water in cold regions, are explained in Section 2. Marine icing models, which were obtained by various experimental, theoretical and numerical methods, are studied in Section 3. These models are categorized based on when the research was conducted. Some significant developments in the modeling and analysis of sea spray icing phenomenon, which are carried out before 1980, between 1980 and 2000, and after 2000, are described in this section. To acquire more accurate and applicable marine icing models, three various issues are discussed in Section 4. These issues are: (1) data acquisition, (2) physical processes in the formation of ice, and (3) marine icing modeling. Conclusions of this review are presented in Section 5.

2. Icing phenomena

Sea spray icing can lead to substantial hazards, including stability problems of marine vessels and to the safety of the crew in cold seas or ocean regions (Cammaert, 2013; Dehghani-Sanij et al., 2017; Feit, 1987; Fukusako et al., 1989; Jørgensen, 1982; Jessup, 1985; Lock, 1972; Lundqvist and Udin, 1977; Rashid et al., 2016; Ryerson, 2008, 2009, 2011; Wiersema et al., 2014). Jessup (1985) expressed that sea spray icing can increase the vessel's weight and lower its freeboard (the distance of the water level from the deck); consequently, icing will raise the center of gravity and decrease the stability. A number of researchers have reported the hazards caused by icing and ice accumulation on marine platforms (Brown and Mitten, 1988; Cammaert, 2013; Jessup, 1985; Jørgensen, 1982; Makkonen, 1989; Nauman and Tyagi, 1985; Ryerson, 2008, 2009, 2011; Schrøder Hansen, 2012). Ryerson (2011) and Cammaert (2013) provided a list of the hazards of the icing phenomena for marine vessels and offshore structures. These hazards are: instability and loss of integrity of marine ships and structures, malfunction of the operational equipment such as winches, derricks and valves as well as communication antennas, slippery handrails, ladders or decks, unusable lifeboats and fire equipment, and the blocking of air vents. Also, the icing problems caused by seawater spray and precipitation for offshore structures were reported by Jørgensen (1982).

According to a report by Jørgensen (1982), atmospheric icing will be created because of the freezing of freshwater in the form of supercooled drizzle or rain, snow or sleet, supercooled fog, and frost spoke. Saha et al. (2016a) reported on the freezing of saline water droplets on cold plates in different situations. They reported that the size and salinity of water droplets, as well as the surface temperature of plates, affect the freezing phenomena significantly. Additionally, Ryerson (2011) reported that atmospheric icing can be categorized as (a) glaze ice, which is the freezing rain, snow and drizzle, (b) hoar frost resulting from the direct deposition of water vapor as ice crystals, as well as (c) rime ice resulting from supercooled cloud or fog droplets. He also expressed that sleet, which is a type of freezing precipitation, is traditionally not categorized as atmospheric icing. Makkonen (2000) showed that atmospheric icing is a result of freezing either by cloud droplets, raindrops, snow or water vapor. Minsk (1977) reported that ice formation by atmospheric precipitation does not usually contain brine inclusions. Also, three major types of ice can form depending on wind velocity and ambient air temperature: glaze, hard rime and soft rime. Table 2 illustrates their properties and occurrence. Moreover, a combination of glaze-hard rime, glaze-wet snow, hard and soft rime, and glaze-soft rime can happen (Minsk, 1977).

Wave-generated and wind-generated spray are the two principal sources of sea spray icing or marine icing in cold seas or ocean regions. Wave spray is generated due to the impact of waves on marine vessels and offshore structures. According to Dehghani-Sanij et al., (2015, 2016, 2017) and Schrøder Hansen (2012), wave spray is ordinarily a large source that is typically a short and approximately periodic water