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Droplet trajectories of wave-impact sea spray on a marine vessel

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ABSTRACT

Marine icing phenomena are strongly dependent on the rate of water impact to marine vessels. The most important source of this incoming water is wave-impact sea spray. There is limited understanding of droplet size and velocity distributions of wave-impact sea spray. Initial distributions of the size and velocity of droplets are crucial for the calculation of the droplet path and consequently for determining the water impact to every individual place on marine vessels. This paper develops a new model of wave-impact sea spray using a distribution of the size and velocity of droplets at the edge of the vessel. The concepts of water-sheet breakup and droplet breakup lead to an inverse dependence between the size and velocity of droplets after the breakup process. Droplets take different paths and form a spray cloud in front of the vessel. The liquid water content in front of the vessel can be calculated by considering the arrangement, sizes, and velocities of a set of droplets in the spray cloud. The response of the droplet trajectory model to various initial conditions with different sets of droplet sizes and velocities is examined. The numerical results are compared to real data from field observations. Droplet sizes are inversely proportional to droplet velocities, as verified by liquid water content data obtained by the field observations. This paper proposes the use of this inverse relationship based on physics of the breakup process as the initial data for calculating the wave-impact sea spray trajectory in front of a vessel.

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1. Introduction

Marine icing phenomena, involving ice accretion and accumulation on vessels, have been significant challenges in offshore technology development. Due to growing expectations about the role of the Arctic in supplying oil and natural gas resources, the importance of marine icing phenomena has increased. Accurate prediction of ice accretion on marine vessels has remained a challenging concern. Researchers have made many efforts in this field, but several aspects of these phenomena are not yet well understood (Kulyakhtin and Tsarau, 2014; Shipilova et al., 2012; Ryerson, 2011).

A sufficient rate of incoming water droplets and a cold climate are enough for marine icing phenomena to start. Atmospheric and sea-generated droplets are two sources of water droplets. Field observations show that atmospheric droplets and humidity, including rain, snow, drizzle, and fog, are not the most significant contributors to ice accretion, and consequently, they are not the main potential causes of ice accretion on marine objects in harsh conditions. These have been analyzed in detail by Makkonen (1984). Sea-generated water droplets have a more significant role in the occurrence of ice creation and accumulation on marine vessels (Lozowski et al., 2000; Zakrzewski, 1987).

Wind-generated spray, which refers to droplets raised from the sea surface by wind, and wave-impact-generated spray, caused by atomized droplets created by wave impact on the outer surface of marine vessels, are two important sources of sea-generated droplets. Wind-generated droplets generally have fewer effects on marine icing phenomena, and they are often neglected in the calculations of ice accretion (Lozowski et al., 2000; Zakrzewski, 1987). Wave-impact-generated droplets are the main cause of ice accretion on marine vessels. In harsh conditions at sea, marine vessels are faced with a high rate of water droplets due to the differing impacts of high-energy waves (Zakrzewski, 1987). Fig. 1 shows a general schematic of the sources of the water droplets delivered to marine vessels and their role in marine icing modeling.

A review of previous studies shows that there are limited field observations on the measurement of the rate of water droplets hitting marine vessels due to wave impact. Some correlations and empirically-based relations have been developed. These relations describe the rates of incoming water of a wave-impact sea spray, which are usually the amounts of water in a unit volume of air, called the Liquid Water Content (LWC). The most significant investigations of wave-impact sea spray are from Borisenkov et al. (1975),Zakrzewski (1987),Horjen and Carstens (1989), and Ryerson (1995). These researchers attempted to extract LWC data from field observations. The vertical distributions for liquid water content have been the most useful data obtained from the field observations. These LWC relations have been used by researchers to predict ice accretion on vessels.

The main focus of this paper is on wave-impact sea spray in front of vessels. There have been a few past works which are directly related to vessels. Borisenkov et al. (1975) showed that the LWC, which results from wave-impact splashes, varies by height from deck level

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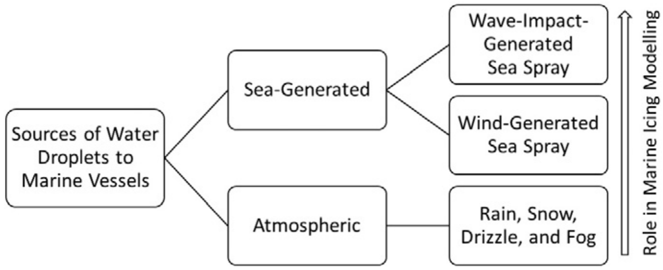

Fig. 1. Sources of water droplets and their role in marine icing modeling.

exponentially. The correlation and model were based on observations in the Sea of Japan obtained for a Medium-sized Fishing Vessel (MFV), which recorded the amount of incoming water to the deck without recording the size and velocity of droplets. The report of Borisenkov et al. (1975) was the first and most significant investigation which is related to vertical distribution of the LWC in front of a vessel.

Zakrzewski (1987) extended the work of Borisenkov et al. (1975) by generalizing the correlation to include all wave conditions. It was assumed that the LWC depends on wave height and that the relative velocity of a wave and vessel can increase the LWC by a power of one and two respectively. The generalized relation was verified by Borisenkov's correlation. Ryerson (1995) included aspects of droplet size distribution and droplet concentration for wave-impact sea sprays. The observations showed that there is a range of droplet diameters from very fine, at 14 μm, to very large, at 7700 μm. In addition, it was reported that the mean droplet concentration was 4×105 drops/m^3. This gives more information than the liquid water content alone.

Calculations and predictions of ice accretion on a surface are strongly dependent on the rate of water droplet impact on every location of that surface on marine vessels. The rate of water droplet impact depends on droplet trajectories from the injection spots, which are the upper edges of the vessel bow, to target surfaces. The gravity force, wind velocity, initial size of droplets, initial velocity of droplets, and many other parameters can affect droplet trajectories and, consequently, the rate of water received on target surfaces (Zakrzewski and Lozowski, 1988). The crucial data for applying a droplet trajectory analysis are droplet size distribution, droplet velocity distribution, and droplet concentration (Dehghani et al., 2009). With this information, the geometry of the vessels or offshore structures, and some atmospheric information, a good estimation of sea water droplet impact on the surface points can be predicted. Therefore, without a sophisticated model for the distribution of the droplet sizes and velocities, it is difficult to accurately predict the rate of droplet water impingement on target surfaces; as a result, the estimation of the amount of accumulated ice will not be accurate.

Past studies have reported relations that explain the vertical distribution of the LWC due to the impact of waves on vessels and offshore structures (Forest et al., 2005; Zakrzewski, 1987; Lozowski et al., 2000). These involve functions of wave specifications, atmospheric conditions and marine object characteristics. Estimating the accumulated ice needs the contribution of the droplet trajectory method to give a good estimation of water delivery to the surface. The velocity and size of droplets are the least information which is needed for that calculation. Past studies have typically assumed droplet sizes, velocities, and concentrations in order to calculate the droplet trajectories and, consequently, the ice accretion results. The theoretical basis of their LWC relations has been discussed, but the basis of their assumptions for choosing the size and velocity of droplets is not clear enough. Lozowski et al. (2000) explained these relations used in RIGICE by assuming the initial vertical and horizontal velocities and initial drop sizes. Other researchers who used the droplet trajectory have not used distributed droplet sizes and droplet velocities. They usually assumed a fixed initial velocity and size for all heights (Shipilova et al., 2012; Horjen, 2013; Kulyakhtin and Tsarau, 2014).

The complete set of data of wave-impact sea spray should include the distribution of droplet size, velocity, and concentration. To date, there has been no work done to describe a wave-impact sea spray considering this essential information. In addition, phenomena related to the creation of wave-impact sea spray have not yet been explained (Zakrzewski, 1987; Lozowski et al., 2000; Shipilova et al., 2012; Horjen, 2013; Kulyakhtin and Tsarau, 2014).

Ryerson (1995) reported the size and concentration of droplets. This was based on the measured samples from some regions of a spray cloud and not a complete distribution data set for the whole spray cloud. Users would need to generalize the suggested distribution for the droplet size and concentration to all regions of the spray cloud. In addition, having an initial velocity distribution for droplets is crucial to obtain the path of a spray cloud on vessel and Ryerson's model did not include the droplet velocity data.

There have been previous investigations into determining the LWC for offshore structures. In those cases, the geometry of the surfaces that waves strike is different from that of the vessel's bow. Their wave-impact sea spray would be different. Forest et al. (2005) reviewed past LWC relations for offshore structures. The exponential form of those relations is the same as the relations for the vessels but they have some significant differences. As mentioned, the most relevant formula for the vertical distribution of the LWC for vessels is a model of Borisenkov et al. (1975), which is developed by Zakrzewski (1987). The formula presented by Borisenkov et al. (1975) is one of the formulae based on real field observations in the Sea of Japan using the MFV. It is at least valid for that special situation, that vessel geometry, and the environmental situation.

In the present work, a new correlation between droplet sizes and velocities at the injection area, the top edge of the bow, is introduced. This size–velocity dependence for droplets aids in the use of LWC information. The new model will be examined in comparison with the LWC from field observations for real vessels (Borisenkov et al., 1975), and a sensitivity analysis will show the effect of various parameters on the output of the model.

2. Wave-impact sea spray

Dividing the marine icing phenomena into two consequent phenomena, called off-deck and on-deck phenomena in this study, will clarify the importance of wave-impact sea spray. The off-deck phenomena are those that occur outside of the marine vessel. These include sea wave creation and movement, sea wave impact on marine vessels, water breakup, and finally droplet dispersion in front of the marine vessel. This set of distributed water droplets in front of a vessel is called wave-impact sea spray. The on-deck phenomena are those which occur on and above the marine objects. The spray and droplet trajectory, droplet impingement on marine objects, start of icing, and ice accretion are the main subdivisions of the on-deck phenomena.

The majority of past research has focused on on-deck phenomena. There have been many reports on ice accretion, which is the final stage of on-deck phenomena. But there is a limited number of studies about the impact of sea water droplets on vessels. It should be noted that the quality and accuracy of the prediction of ice accretion is strongly dependent on the rate of incoming water droplets on marine vessels. The estimation of off-deck phenomena is a prerequisite for accurate prediction of on-deck phenomena. But off-deck phenomena are lesser-known parts of the marine icing phenomena. Fig. 2 illustrates the classification of marine icing phenomena based on the above-mentioned description.

A review of past research related to wave-impact sea spray for a vessel's bow shows that this field of research was initially pursued with field observation data (Borisenkov et al., 1975). There are variations of LWC for various heights, vessel speeds, heading angles, wind speeds, wave specifications, sea water temperatures, wind temperatures and some other information related to the icing situation. These

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