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A review of numerical modelling techniques for marine icing applications

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ABSTRACT

Ice accretion reduces the stability, reliability, productivity, and safe operation of offshore exploration vessels, icebreakers, and marine structures in Arctic regions. This paper presents a review of existing literature on ice accumulation on marine vessels and offshore structures. Existing reports for field measured icing data are reviewed, which reveals that wave-collision generated sea spray is the main source of marine icing. Fundamental knowledge of different heat fluxes on the icing surface are analyzed and several numerical techniques for modelling of icing predictions on vessels, drilling rigs, and other offshore structures are critically reviewed. Additionally, this paper identifies methods of improving the ice prediction rate for marine vessels and offshore structures.

Nomenclature

Variable	Units	Description
b	m	Thickness of accreted ice
$\frac{db}{dt}$	–	Growth rate of ice dendrites
c_p	$J\,kg^{-1}\,K^{-1}$	Specific heat of dry air
c_w	$J\,kg^{-1}\,K^{-1}$	Specific heat of water
e_a,e_s	–	Saturation vapor pressure of moist air
h	$J\,kg^{-1}$	Enthalpy
h_c	$W\,m^{-2}\,K^{-1}$	Local convective heat transfer coefficient
I_x	–	Base dimension
I_y	–	Base dimension
k_w	$W\,m^{-1}\,K^{-1}$	Thermal conductivity of water
L_f	$J\,g^{-1}$	Latent heat of fusion of pure ice
l_f	$J\,g^{-1}$	Latent heat of fusion of pure ice
$l_f\,(1-\sigma_M)$	$J\,g^{-1}$	Latent heat of fusion of the saline ice accumulation
l_v	$J\,g^{-1}$	Latent heat of vaporization of water
M	$kg\,m^{-2}\,s^{-1}$	Total water flux
M_{evap}	$kg\,m^{-2}\,s^{-1}$	Mass flux of evaporation
M_{ice}	$kg\,m^{-2}\,s^{-1}$	Mass flux of ice
M_{runoff}	$kg\,m^{-2}\,s^{-1}$	Mass flux of runoff
n	–	Accretion fraction
p	$kg\,m^{-1}\,s^{-2}$	Atmospheric air pressure
Pr	–	Prandtl number
Q_c	$W\,m^{-2}$	Convective heat flux from the air to the water film surface
Q_{cond}	$W\,m^{-2}$	Conduction heat transfer
Q_{conv}	$W\,m^{-2}$	Convection heat transfer
Q_d	$W\,m^{-2}$	Heat capacity of the spray impinging to the surface of accreted ice
Q_e	$W\,m^{-2}$	Evaporative heat flux from the air to the water film surface
Q_{evap}	$W\,m^{-2}$	Evaporation heat flux from the outer surface to the airstream
Q_{im}	$W\,m^{-2}$	Heat flux in cooling the seawater from the sea temperature to the freezing point for the water which remains accreted to the surface
Q_{lat}	$W\,m^{-2}$	Latent heat flux released at the outer ice surface due to freezing
Q_r	$W\,m^{-2}$	Radiant heat flux from the air to the water film surface
Q_{rad}	$W\,m^{-2}$	Energy flux due to radiative transfer
s	–	Significant or s-direction
S_c	–	Schmidt number
S_{sp}	ppt	Salinity of the spray water
S_{sw}	ppt	Salinity of the brine
S_w	ppt	Salinity of water film on the surface of the accreted ice
T_a	K	Temperature of the air
T_d	K	Droplet temperature immediately prior to impingement
T_{es}	K	Temperature of the water film at the air-

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		water interface
T_f	K	Freezing temperature of the water film
T_{sw}	K	Brine temperature
T_w	K	Water-film temperature at the air-water interface
x	m	Distance from the sea wall
δ	m	Brine film thickness
ϵ	–	Ratio of the molecular weights of water vapor and dry air
ς	–	ς-direction
η	m	Water film thickness
$\frac{d\eta}{dt}$	–	Time derivative of water film thickness
ρ_b	$kg\ m^{-3}$	Density of brine
ρ_i	$kg\ m^{-3}$	Density of the accreted ice
ρ_{ice}	$kg\ m^{-3}$	Density of the ice
σ_M	–	Interfacial distribution coefficient, ratio of unfrozen water mass entrapped into the ice accretion to the mass of the ice accretion

1. Introduction

Icing poses serious hazards to Arctic offshore applications. While operating in Arctic waters, marine vessels and offshore structures often experience operational and safety problems (Makkonen, 1984a; Ryerson, 2009, 2011). Numerous ship losses due to icing have been reported by Aksyutin (1979), DeAngelis (1974) and Shellard (1974). An overview of available literature indicates that the first systematic research on vessel icing was conducted in the United Kingdom in 1957, after losing two British steam trawlers, the Lorella and Roderigo, during an icing storm (Trawler Ic. Res., 1957; Zakrzewski and Lozowski, 1991). Later, Japan, the Soviet Union and Canada lost several vessels in the cold waters of the Sea of Japan and Bering Sea, North Pacific Ocean and Alaskan waters (Zakrzewski and Lozowski, 1991). These losses caused the launching of several organizations, such as the British Shipbuilding Research Association, Japanese Research Program, Soviet Program, US Army Cold Regions Research and Canada's National Research Council. These organizations investigated ice accretion mechanism on vessels, develop vessel icing forecasting techniques, collect field data, and examine the effect of ice loads on vessel safety and stability (Sawada, 1968; Zakrzewski and Lozowski, 1991). Their research revealed that icing due to the freezing of wave-generated sea spray is the main source of vessel icing (Borisenkov and Panov, 1972; Panov, 1976; Shekhtman, 1967, 1968). Currently, Bodaghkhani et al. (2016) reviewed sea spray dynamics that can cause marine icing. Additionally, Saha et al. (2016a) conducted experiments to show the behaviour of water jets after their impact on a vertical surface. Furthermore, Dehghani et al. (2016a, 2016b, 2017a) modeled the movement of sea spray clouds using trajectory analysis, breakup phenomena and size-velocity dependence characteristics.

During cold climate conditions, vessels and offshore structures can experience atmospheric icing and sea spray icing (Makkonen, 1984a). Borisenkov and Panov (1972) analyzed data from over 2000 icing events on Soviet fishing vessels, and reported that 89.8% of those icing events occurred due to sea spray alone. Additionally, 6.4% occurred due to sea spray combined with fog, rain or drizzle, 1.1% occurred due to sea spray with snow, and 2.7% occurred due to atmospheric icing. Brown and Roebber (1985) analyzed some data from Canadian ship meteorological reports, and found that a frequency range of 81% to 97% is provided for icing due to sea spray for some regions of the Canadian East Coast. Additionally, a range of 1% to 17% is given for icing from atmospheric sources. Although the effect of atmospheric icing is minor, it still needs to be considered (Makkonen, 1984a). Makkonen (1984a) explained that the accretion of atmospheric icing does not decrease with elevation, whereas sea spray is affected by height.

Sea spray icing is restricted to lower heights and surfaces such as decks, derricks and handrails. Sea spray does not usually reach higher than approximately 16 m above the sea surface (World Meteorological Organization, 1962). Dehghani et al. (2016b, 2017a) showed that the maximum height of spray cloud for a medium-sized fishing vessel in the Sea of Japan is about 8.5 m. Therefore, the importance of atmospheric icing is that it typically occurs on the upper parts of the vessels, includes masts and antennas, among others (Makkonen, 1984a). Over the past 40 years, researchers have published several studies to address the complexity of vessel icing (Lozowski et al., 2000; Lozowski and Gates, 1991; Lozowski and Makkonen, 2005; Zakrzewski and Lozowski, 1991).

The aim of this paper is to present a state-of-the-art review of existing literature related to ice accumulation on marine vessels and offshore structures. Various meteorological and oceanographic factors that influence vessel icing are described in Section 2. To predict the icing rate on an object's surface, a heat balance model is required, as presented in Section 3. In Section 4, a comprehensive study of current marine icing models is presented.

2. Fundamentals of icing

Icing can be categorized into two types: fresh water or atmospheric icing and sea water or sea spray icing (Makkonen, 1984a). Atmospheric icing is mainly dangerous for aerospace and power transmission industries (Makkonen, 1984b; Sundin and Makkonen, 1998). Sea spray icing is hazardous for offshore vessels and structures (Makkonen, 1984a, 1987). Atmospheric icing normally occurs due to meteorological aspects, such as air temperature, wind speed, and liquid water content (Kraj, 2007; Minsk, 1980). Sea spray icing occurs due to wave generated spray and wind generated spray (Zakrzewski, 1986b).

Atmospheric icing can be divided into three categories: precipitation icing, in-cloud icing and hoar frost icing (Boluk, 1996; Fikke et al., 2006; ISO-12494; Richert, 1996). The cause of precipitation icing is rain or drizzle, which may result in dry or wet snow and glaze formation (Farzaneh, 2008; Feit, 1987b; Parent and Ilinca, 2011). In-cloud icing occurs due to extremely low temperature conditions, when small super-cooled liquid droplets in clouds immediately freeze after impact on the surface (Blackmore, 1996; Parent and Ilinca, 2011). This type of icing can be categorized into two forms: rime ice and glaze ice (Ilinca, 2011; Makkonen, 1984a; Minsk, 1980; Parent and Ilinca, 2011; Wang, 2008). Rime icing is further divided into hard rime and soft rime. Hard rime is caused by slower heat loss and soft rime is caused by quicker heat loss (Makkonen, 1984a; Minsk, 1980). Glaze ice is a kind of smooth, homogeneous and transparent ice (Makkonen, 1984a; Wang, 2008). This type of ice forms when droplets stay in a continuous film on the surface before freezing (Minsk, 1980). Lastly, hoar frost icing is mainly formed due to water vapor sublimation to ice (Makkonen, 1984a, 2000; Minsk, 1980).

Sea spray or marine icing is caused by two sources: wind spray and wave spray. DeAngelis (1974) reported that moderate icing mainly occurs with high wind speeds such as 6.5 m/s or more. Generally, wind spray is caused by droplets blowing off whitecaps on the ocean surface and remaining in the air for all wind conditions with constant water flux (Hansen, 2012; Jones and Andreas, 2012). Wave spray is caused by the collision of a vessel or offshore structures with waves (Hansen, 2012). Medium-size droplets can reach higher on a vessel compared to small and large droplets (Dehghani et al., 2016a, 2016b). A collision can send a brief and periodic freezing spray flux onto the surface of the vessel, which creates icing (Hansen, 2012; Ryerson, 1995). In earlier publications, researchers reported that wave-generated sea spray is the most dangerous icing source for offshore vessels (Aksyutin, 1979; Brown and Roebber, 1985; Cammaert, 2013; Chung et al., 1995b; Kato, 2012; Makkonen, 1984a, 1984b; Ryerson, 2011; Shekhtman, 1968; Shellard, 1974; Tabata et al., 1963; Zakrzewski, 1986a, 1986b, 1987).