SEA SPRAY ICING OF SHIPS AND OFFSHORE STRUCTURES

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Contents

Summary

Marine icing is a component of the broader subject of ice accretion, also known as "icing", which occurs in the marine environment. Ice accretion is the accumulation of ice on an object in a cold environment, as a result of the impingement of airborne liquid water droplets, ice particles and snow particles, or the deposition of water vapor. Examples include atmospheric ice accretion on trees, communication towers and power lines; in-flight icing on aircraft components; the growth of hailstones; and icing on ships and offshore structures as a result of the impingement of a spray of brine drops, fog or precipitation. Marine icing can be subdivided into two main categories depending on the source of the impinging liquid. If the source is the ocean, it is called sea spray icing. If the source is atmospheric (hoar frost, freezing fog, freezing rain, freezing drizzle or wet snow), it is referred to as atmospheric icing in the marine environment. This chapter focuses on sea spray icing. The ocean is the source of the impinging drops. Atmospheric icing resulting from the accretion of fog droplets, freezing raindrops and wet snow can also occur in the marine environment, but it is not considered here.

1. Introduction

For generations, sailors have feared marine icing, or "white mist", as it is called. Heavy, battering waves accompanied by gale-force winds, sheets of spray and suddenly dropping temperatures can be a deadly combination. Without warning, layer upon layer of ice forms relentlessly on anything touched by the spray, rapidly coating the vessel with thick sheets of ice that reduce maneuverability and threaten its stability. Offshore structures are also susceptible.

Icing in the marine environment may be defined as the accumulation (accretion) of ice on ships, offshore structures and coastal facilities, as a result of the impingement and freezing of liquid in the form of spray, fog, drizzle and rain, or ice in the form of snow or wet snow. It is usually most severe with spray accretion produced by wave impact on the structure or vessel, or arising from drops ejected or removed from the ocean surface as a result of the action of the wind on the waves. This form of icing is referred to as “sea spray icing”.

Sea spray icing is illustrated in Figures 1 and 2. The Canadian Coast Guard Ship “Sir William Alexander” (length 83 m, beam 16 m, gross tonnage 3700 t) encountered severe icing offshore the Canadian Province of Nova Scotia on January 25 and 26, 2004. The environmental conditions were: air temperature -12°C to -16°C, wind speed 30 to 40 knots, sea state Beaufort 6 to 8, significant wave height 1 to 4 m, vessel speed 9 to 14 knots. The estimated ice characteristics were as follows: total ice load 200 to 300 t, maximum ice thickness 35 cm, and maximum ice height on the mast 15m. The vessel was de-iced twice during the event and once in port after the event. The final de-icing required two days.

In this chapter, we consider the climatology of marine icing, its effects on ships and offshore structures and the regulatory framework for vessel design and operation. We summarize the physical properties of sea spray ice accretion and the methods that have been used to attempt to mitigate it. We then review the physical processes that give rise to sea spray icing and how they have been used to create both simple and complex models of icing. Finally, we see that, despite our understanding of sea spray icing and our ability to model it, it is still difficult to satisfactorily forecast the icing risk for all mariners and offshore operators.

2. Occurrence and Effects of Sea Spray Icing

Typical relative icing frequencies on fishing vessels, according to the source of impinging liquid, are as follows: spray alone (90%), spray with simultaneous atmospheric icing (7%), atmospheric icing alone (3%). In Arctic seas, atmospheric icing plays a larger role.

Here the statistics are: spray alone (50%), spray with simultaneous atmospheric icing (41%), atmospheric icing alone (9%). Hence, sea spray, either alone or in combination with atmospheric hydrometeors, is the most frequent cause of ship icing. Sea spray icing is also cited as the most frequent cause of ship losses, although there are indications that the accumulation of ice due to freezing fog over long periods can be dangerous too, due to the high centre of gravity of the ice accretion.

Sea spray icing can occur anywhere the air and sea surface temperatures are sufficiently cold and wave height and vessel speed are sufficiently high to produce impact spray. However, the most severe and frequent icing tends to be associated with synoptic-scale weather systems (extratropical cyclones) that produce cold air outbreaks over coastal ocean areas. Regions with documented higher risk include Canada's East Coast, the Gulf of Alaska and Pacific coastal fjords, the Baltic Sea and the Barents Sea. As the cold air streams offshore over a warmer ocean, icing intensity increases initially as wave height increases. Still further offshore, icing intensity typically begins to decline as the cold air is warmed by the ocean surface.

Figure 1. Icing of the Canadian Coast Guard Ship "Sir William Alexander", during a 34-hour icing event offshore the Canadian Province of Nova Scotia, on January 25-26, 2004 (details in the text). The photograph shows plumes of spindrift spray (spume) coming off the waves and collision-generated spray coming over the bow.

The effects of sea spray icing depend on the type and size of vessel or structure on which the ice accumulates. Small ships such as fishing vessels are particularly vulnerable. But whatever the vessel or structure, icing can be dangerous. Icing on lifesaving and firefighting equipment is a potential safety hazard. A severe ice buildup can block vents and scuppers, obscure bridge windows and seize up deck equipment, such as masts, cables, hatches, winches, davits, sheaves, windlasses, anchors, valves, booms, derricks, cranes, containers, rigging, stays, and radar and communication antennas. It can also render decks, ladders and handrails slippery or unusable. When ice accumulates on antennas, it can interfere with navigation, communication and hazard identification. The most serious consequence of ice accretion on floating vessels, however, is its effect on the vessel's maneuverability and stability, as determined by the overall ice load and its distribution over the vessel. Icing loads increase the draught, reduce the freeboard and raise the centre of gravity of the vessel. If the vessel is moving into the wind and waves, ice accumulation is greatest on the vessel's foreparts, leading to greater bow immersion and enhanced shipping of green water and spray. In extreme cases, the propeller and rudder may rise above the sea surface, limiting maneuverability and control. Beam winds and waves produce an asymmetrical accretion, leading to listing of the vessel and increasing its tendency to capsize as a result of the raised centre of gravity. Icing also enhances the sail area of the vessel and hence the wind-induced heeling moment.

Figure 2. Icing of the Canadian Coast Guard Ship "Sir William Alexander", during a 34-hour icing event offshore the Canadian Province of Nova Scotia, on January 25-26, 2004 (details in the text). The photograph shows the icing on the buoy deck. Icicle formation is evident as are the de-iced stairway to the foredeck and the de-iced, open hatch.

The height to which wave-impact spray rises depends on the kinetic energy of the collision, and hence on vessel and wave speeds. Bow design, particularly bow flare, also influences the amount of spray that rises above the bulwarks. Except for high-speed vessels, it is rare for sea spray icing to reach more than about 15m above the sea surface. Hence, spray icing is most dangerous for small vessels, of less than 1000 t displacement, or those with a relatively low freeboard such as heavily laden tankers. For small vessels, the ratio of superstructure surface area to displacement is large. As a result, the ratio of the vessel's capacity to accrete ice to its capacity to sustain an ice load is also large. For small vessels, it has been suggested that the danger of capsizing is imminent, when the ice load approaches 15% of the vessel's un-iced displacement. This rule of thumb is appropriate for head winds and seas. With beam winds of 30°, this value is reduced to less than 10%.

3. Observations and Climatology

The International Maritime Meteorological Code of 1995 allows for a basic reporting of icing on ships. Provision is made for the reporting of icing source (ocean spray, fog, spray and fog, rain, spray and rain), icing thickness and icing rate (not building up, building up slowly, building up rapidly, melting or breaking up slowly, melting or breaking up rapidly). Plain language comments can also be inserted into the code.

Various researchers have devised or analyzed marine icing questionnaires or reporting forms that have been distributed to vessel captains. Such surveys have been very helpful in establishing what we know about icing climatology and its geographical distribution. They have also been useful in the creation of empirical, statistical models for forecasting marine icing. However, there are no internationally recognized instruments for measuring the rate of marine icing. Without standardization and specificity (e.g. icing amount and rate are usually estimated rather than measured, and location on the vessel may not be specified), such surveys have been of limited usefulness in the formulation and evaluation of marine icing models and forecasts. Recently, an automated marine icing detection and monitoring system was developed at the National Research Council of Canada. It has been field tested on several vessels and it has the potential to be used widely as a systematic tool for recording and quantifying marine icing.

Only rarely have quantitative ship icing measurements been made with instrumented research vessels and scientists on board. These include a Japanese research program in the 1960's, a Russian research program in the late 1960's and early 1970's, a brief Canadian measurement program in February 1988 and a program sponsored by the US Navy in the 1990's. While these data sets are more detailed and of higher quality than the questionnaire data, they are still incomplete in various ways and therefore of limited use in the formulation and evaluation of marine icing models and forecasts. Icing data sets for offshore platforms are even more rare.

Because of the scarcity of marine icing data, marine icing risk maps based on observations, must be considered provisional. Nevertheless, several investigators have produced maps of ship icing probability or potential, based on meteorological and oceanographic conditions, for various Polar Regions. Some have been produced with the aid of simple algorithms (e.g. wind speed > 8 ms^{-1}, air temperature < 2°C), while others are based on more complete models of the icing process. All are based on climatological values of the underlying parameters, but these fields may vary from source to source. They may also change with time as a result of global warming. As a result, the various maps are not in complete agreement and their current reliability is uncertain.

An interesting new development is the creation of synthetic marine icing risk maps, by driving a simple icing model with environmental data derived from meteorological re-analysis fields. These maps have the advantage of avoiding icing data gaps and potentially allowing for the effects of climate change. Figure 3 is such an icing climate map, produced by Kent Moore of the University of Toronto. It shows regions of light

(<0.7 cmh^{-1}), moderate (0.7 to 2.0 cmh^{-1}), heavy (2.0 to 4.0 cmh^{-1}) and extreme (>4.0 cmh^{-1}) icing rates in the sub-polar North Atlantic.

Icing rate depends on vessel size, architecture and superstructure details. There are reports of icing rates as high as 20 cm h^{-1} on Norwegian capelin seiners. In the Soviet literature, icing rates are frequently quoted in t h^{-1}. This is because much of the icing data has been measured for a "standard" medium-tonnage fishing trawler of displacement 400 t. For such a vessel, the IMCO-designated sustainable ice load corresponds to 10.6 t of ice (2.7% of un-iced displacement). The highest measured icing rates for these vessels were about 16 t h^{-1}. The maximum reported ice load on such a vessel was 54 t (13.5% of un-iced displacement). There is a report of a 630 t stern trawler with an estimated ice load of 200 t (32% of un-iced displacement), following a 40-hour icing storm.

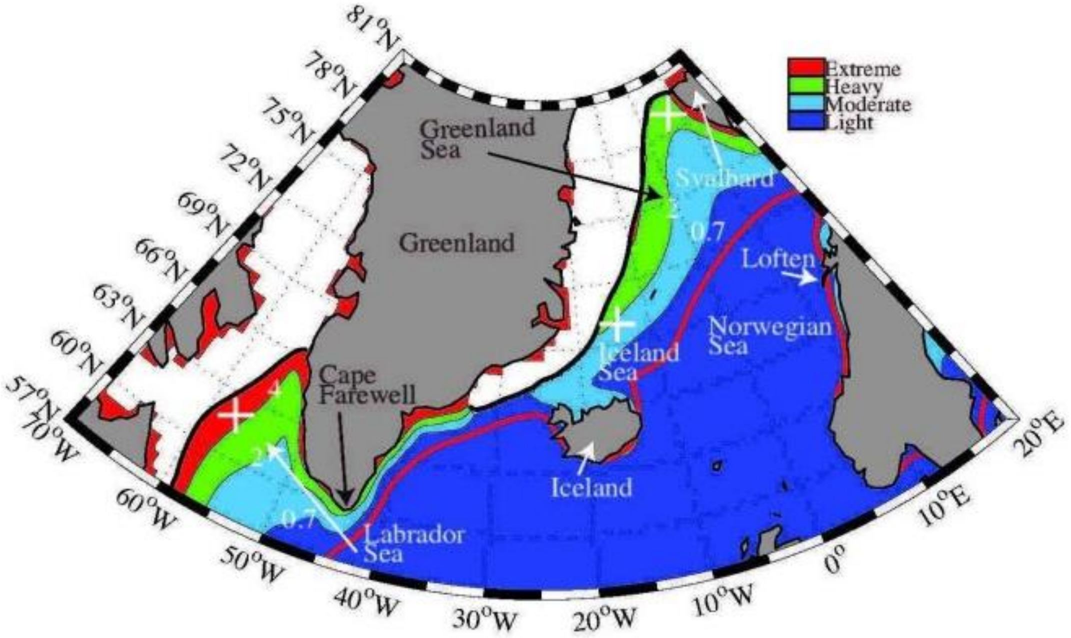

Figure 3. Synthetic climate map of vessel icing rate over the sub-polar North Atlantic during winter (December, January, February, March). After Moore (2013).

4. Some Notable Severe Icing Events

On the night of February 18, 1966, the side trawler "Blue Mist II" (length 37m, displacement 330 t) sank and its crew disappeared about 60 km west of Cape Anguille, Newfoundland. It is believed that stormy seas and severe icing were the causes of the disaster. Transport Canada has estimated that the conditions at the peak of the storm were: air temperature -18°C, dew point temperature -22.4°C, air pressure 100 kPa, sea-surface temperature 0°C, wind speed 30 ms^{-1}, wind direction 270°, significant wave height 7.7m, significant wave period 10.9 s, sea-surface salinity 3.3%, no precipitation.

Because of their large freeboards and substantial reserve stability, it was thought that icing was not a serious problem for larger vessels. However, on December 8, 1989, the

90 m bulk carrier “Johanna B” and the 130 m container ship “Capitan Torres” were lost due to icing in the Gulf of St. Lawrence.

In-situ icing measurements on offshore platforms are scarce. The general lack of reports suggests that either icing measurements are not made, significant icing does not occur (there have been no recorded losses of floating offshore platforms due to icing), or the operators would prefer to think that icing is not a serious problem. Nevertheless, there are three well-documented reports of severe icing events on offshore platforms. The first occurred on the semi-submersible “Ocean Bounty” in the Lower Cook Inlet, Alaska, during the winter of 1979-80. The second event occurred on the semi-submersible “Sedco 708” on the North Aleutian Shelf, during the winter of 1982-83. The third is a severe icing event on the semi-submersible “Sedneth II”, which began on February 25, 1970.

Perhaps the most severe icing incident reported on any offshore platform was that for the “Ocean Bounty”, which operated about 20 km from shore in the Lower Cook Inlet, during the winter of 1979-80. This vessel has a deck of size 107m x 81m, and it rises 37m from sea level to the main deck. With a displacement exceeding 30,000 t, it accreted over 500 t of ice under the following conditions: air temperature -13 to -16°C, mean wind speed 45 ms^{-1}, peak wind speed 60 ms^{-1}, significant wave height 2.7m to 4.9m, maximum wave height 9.8m, icing duration 169 hours, and a mean icing rate in excess of 20 cm/day. In order to maintain stability near the end of the icing event, the crew was forced to discharge a significant amount of drilling mud. It is thought that the magnitude of this icing event was due in part to the strength of the winds, which are funneled and intensified by nearby mountain valleys. Consequently, it was believed for some time that such an extreme icing event might be unique to this particular geographical location.

This impression was reinforced by a much less intense icing event on the “Sedco 708”, operating on the North Aleutian Shelf at a latitude similar to that of the “Ocean Bounty”, but away from the wind channeling effects of the Lower Cook Inlet. This icing event occurred during the period January 7 to 8, 1983. It resulted in an estimated 31 t of ice accumulated, with a maximum thickness of about 13 cm on the diagonal trusses below the main deck in the central part of the structure. Table 1 compares the “Ocean Bounty” and “Sedco 708” events, reinforcing the importance of wind speed and event duration for the total accumulated ice load.

That the “Ocean Bounty” icing event was indeed not unique or limited geographically, is evidenced by the “Sedneth II” icing event, which began on the evening of February 25, 1970 on the Scotian Shelf, offshore the Canadian Province of Nova Scotia. Although the “Sedneth II” was a smaller vessel than the “Ocean Bounty” with a deck area of 83 x 73 m and a displacement of 17,000 t, it was estimated that between 175 and 200 t of ice accumulated on this rig during the incident. The environmental conditions were: wind speed 22ms^{-1}, 4.6m seas with 3 to 3.7m swells, air temperature -9.4 to -15.0°C, icing duration about 24 hours, yielding a mean icing rate of about 8 t h^{-1}. As for the “Sedco 708”, most of the ice accretion was observed to occur on the diagonal members supporting the main legs. During the most severe period, the ice load increased so quickly that the draft was increasing at a rate of about 30 cm h^{-1}. After the maximum load had been accreted, the rig came within 15 cm of its maximum draft, and the crew was preparing to dump 380 t of mud and barite and 104 t of piping. Fortunately, the storm ceased and this did not have to be done.

Conditions	**Ocean Bounty**	**Sedco 708**
Maximum wave height (m)	9.8	14.3
Significant wave height (m)	2.7 to 4.9	2.6 to 5.6
Air temperature (°C)	-12.8 to -16.1	-7.3 to -12.4
Sea-surface temperature (°C)	5.6	3.4 to 3.7
Wind direction (degrees)	290 to 300	314 to 335
Average wind speed (m s^{-1})	45	18 to 21
Peak wind speed (ms^{-1})	60	28
Icing duration (h)	169	31
Total accumulation (t)	500	30
Mean icing rate (t h^{-1})	3	1

Table 1. Comparison of the “Ocean Bounty” and “Sedco 708” icing events.

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Biographical Sketch

Edward Lozowski obtained his PhD in Physics at the University of Toronto in 1970. Following a postdoctoral year in the Department of Applied Mathematics and Theoretical Physics at Cambridge, he joined the University of Alberta as Assistant Professor in 1971. His research has involved all aspects of ice accretion, including hail, in-flight icing, power line icing and marine icing, as well as ice friction. He retired as Full Professor in 2004, but he continues to engage in research, sponsored by the Natural Sciences and Engineering Research Council of Canada, as Professor Emeritus. He also engages in meteorological and ice consulting, and he provides expert advice to business and the legal community.