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Full-scale tests of deicing with seawater

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ABSTRACT

Sea-spray icing is one of the major hazards for small- and medium-sized vessels in polar regions. Predominant anti- and deicing measures include prevention by heeding the weather forecasts and avoiding high-risk situations, protection by enclosing exposed and high-priority areas, manual ice removal by personnel, heat tracing and surplus heat. Energy is in limited supply on vessels, and alternative ways of ice protection are sought after. Seawater is readily available, and as evident from wave-washing, either naturally occurring or increased by provocative maneuvering, seawater can hold an efficient deicing capacity. This study contains knowledge gained from four separate full-scale deicing tests. Deicing is achieved during the field tests by utilizing the vessel's external fire sprinkler systems and in one case a fire hose. To the author's knowledge, no recent tests with deicing of vessels using flushing seawater have been performed, and this article is considered a first step towards evaluating the viability of the method. Targeted high-volume, low-pressure systems seem to be an effective method for deicing, particularly combined with favorable design. However, because of the risk of increased icing or freezing run-off the method is suitable for vessels and structures with sufficient run-off capabilities. Vessel safety can be improved by incorporating the proposed method.

1. Introduction

Sea-spray icing is a challenge for small- to medium-sized vessels by obstructing operations or compromising vessel safety by, that is, blocking access to equipment, restricting visibility, blocking communication equipment, and creating hazardous outdoor working environments (Deshpande et al., 2021). In extreme cases, the added load can affect the stability of the vessel and cause capsizing (Shellard, 1974). Many ships have been lost at sea during sea-spray icing conditions (Samuelsen, 2017; Panov, 1978). Onega, a Russian fishing vessel was shipwrecked in the Barents Sea in December 2020 with 19 people onboard. The accident was blamed on icing and heeling of the vessel as the crew pulled its fishing net out of the water (Interfax, 2020). Sea-spray icing is foremost associated with the polar regions, but exceptions occur with fatal consequences, such as the six fishing vessels lost off the coast of Denmark in 1979 (Johansen et al., 2020).

Metocean parameters and vessel characteristics largely influence the severity of icing events, and vessel size, wind speed, air and water temperatures are driving parameters (Overland et al., 1986). Sea-spray icing occurs when water droplets impinge on the vessel and freeze, which happens when they are cooled below the freezing point of seawater. In the international standard for Arctic offshore structures, ISO 19906, the icing factors air temperature, wind speed and water temperature are combined and linked to an anticipated icing rate, see Table 1 (ISO, 2019). The icing rates give an indication of the ice removal rate needed to combat icing challenges. However, the guideline does not specify the worst-case scenario.

A highly recommended strategy to deal with sea-spray icing is to plan operations in accordance with the weather forecasts to avoid potentially dangerous icing conditions. Another option is utilizing design solutions that prevent ice accumulation, i.e. enclosing exposed areas, elevating the deck above the spray zone, ensuring efficient run-off, or choosing a hull design that reduces spray. Deicing methods that do not require personnel, such as heating, are preferable. Manual ice removal with mallets or hoses endangers personnel, is limited to areas accessible, and is less time efficient (Deshpande et al., 2021). Removing accreted ice is a challenge, no efficient low-energy solution with low environmental impact is known. Using chemicals for ice removal involves health and environmental considerations and adding heat demands energy. In a recent review of anti-icing/deicing techniques, the authors stated that vessels are often plagued by ice even though timely measures are taken by the crew, due to fast icing and the low efficiency of existing techniques (Zhou et al., 2022).

In sea-spray icing research, reports from fishermen of icing events

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Table 1
Guidelines for sea-spray icing rates on vessels and structures A.6.3.5.3 in ISO 19906 (ISO, 2019).

Seaspray icing	Air temp	Wind speed	Water temp
Slow icing (<10 mm/h)	0° to −3 °C	Any	< 8 °C
	< −3 °C	<7 m/s	< 8 °C
Fast icing (between 10 and 30 mm/h)	−3 to −8 °C	7–15 m/s	< 8 °C
Very fast icing (>30 mm/h)	< −8 °C	>15 m/s	< 8 °C

constitute the basis of most models of ice prediction. The simple observations combined with existing weather conditions have so far provided valuable information for researchers in a field where few scientific tests have been performed. Sea-spray icing conditions appear over vast areas which makes gathering scientific full-scale data difficult, in addition to the challenges of measuring water flux and other parameters on a moving vessel. The complex nature of the freezing interface with numerous parameters challenges modeling, and full-scale tests are essential to verify results. In a field where few experiments exist, even rudimentary tests can be useful. Concerning deicing methods, fishermen, in particular, have experience as the smaller vessels are more exposed to icing. It is valuable to transfer knowledge from the people working regularly under icing conditions on their strategies for ice management.

In heavy seas, large amounts of incoming water, i.e., shipped water or green water, can prevent or remove sea-spray icing on areas of the vessel. In an interview, a former fisherman operating in the Barents Sea shared his experience of deliberately steering the vessel into the largest waves to remove accumulated ice (Skarheim, 2023). Deliberate ship maneuvers can increase spray flux and the amount of shipped water, but the method can be hazardous. Flushing seawater is also used to prevent icing, according to the captain of a snow crab fishing vessel, a common practice during deck operations is to leave the fire hose to flood the deck, which prevents icing (Birkeland, 2023). Fig. 1 shows that the vessel's superstructure is subject to icing, but the majority of the deck remains ice-free. Seawater is an abundant and sustainable resource and experience suggests it could be a method for ice management at sea.

Deicing with seawater is effective if the incoming flux is large enough for the latent heat of this water to avoid freezing and contribute to the melting of ice already formed. It is also crucial that the excess water is efficiently drained from the vessel. Ryerson (2008) mentioned tests of deicing with large volumes of seawater in the 80s in his extensive assessment of superstructure ice protection, but recent experiments with this approach have not been found in the literature. The criteria for success of deicing or anti-icing can vary. In slow icing conditions maintaining operations can be the goal, as well as not accumulating ice. In very fast icing conditions, the success criterion could be safe removal of the vessel from the area with hazardous weather conditions. High-priority zones need special attention in planning deicing procedures, such as areas important for navigation (i.e., windows, communication equipment, steering), evacuation (i.e., lifeboats and exits), and other essential functions such as ventilation. The preferred method for deicing will depend on the success criteria and metocean conditions.

The main objective of this paper is to present results from four full-scale measurements of deicing with flushing seawater. Evaluating the potential of the concept is the first step towards developing the method and applying it to vessels and marine structures.

2. Full-scale tests of deicing with seawater

This paper investigates removing ice with seawater. Fire-protected lifeboats have an external seawater distribution system that envelopes the vessel surface with a water film, this system is therefore beneficial to test ice removal. Lifeboats from two different manufacturers were tested. In addition, a fire hose from a marine service vessel was used to remove ice from a floating jetty. The method of ice accumulation, ice thickness, water distribution system, metocean conditions, etc., varied between tests. A summary of the initial conditions, test conditions, and list of equipment is summarized in Tables 2 and 3. Further, the paper

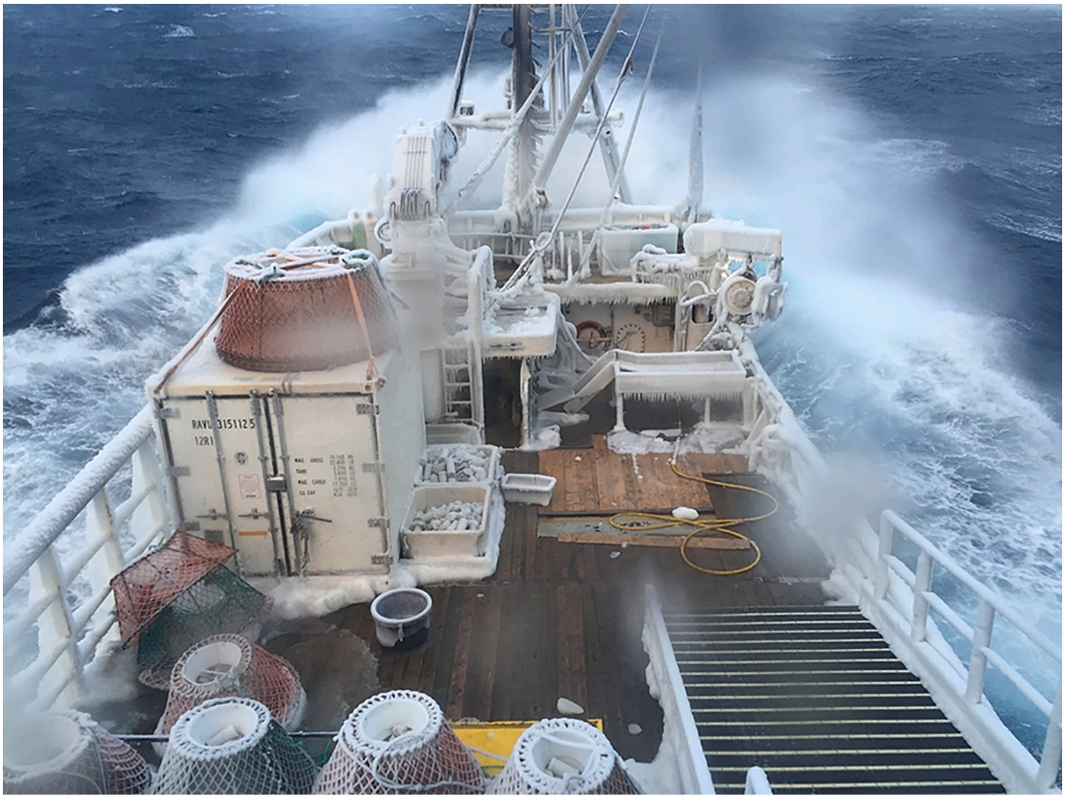

Fig. 1. Anti-icing measure on the M/S Northeastern traveling in sea-spray icing conditions (Birkeland, 2023).

Table 2
List of initial conditions and test conditions. For the test of the Palfinger FF1200 lifeboat the metocean conditions for ice build-up and solidification time are recorded separately, and the latter values are in parenthesis.

Test/Property	Viking Norsafe Miriam 8.5	Viking Norsafe Miriam 8.5	Palfinger FF1200	Floating jetty
Location deicing	Narvik Marina	Narvik Marina	Narvik Harbor	Sildvik
Surface area topside	36	36	126	11
Ice build-up and solidification phase				
Average air temperature [°C]	−7.4	−4.8	−9.2 (−12.4)	−8.1
Average wind speed [m/s]	0.9	1.2	9.7 (2.2)	3.8
Average relative humidity	72	48	67 (69)	59
Sum precipitation [mm]	0	0	0	0.1
Method of ice accumulation	Seawater manually applied	Seawater manually applied	Sea-spray icing	Sea-spray icing
Time interval from adding ice to start of deicing test [h]	24	1.75	21	>72
Initial ice thickness side/focus area [mm]	10	3	–	55
Initial ice thickness roof/remaining dock [mm]	17	45	–	100–220
Deicing test				
Seawater temp. Deicing [°C]	3.5	1.9	3.5	4.6
Air temperature deicing [°C]	−9.2	−3.5	−8.7	−3.5
Seawater salinity ppt	26	25	31	26
Ice salinity ppt	15	–	–	10
Total test duration [min]	32	15	16	31
Time for ice removal focus area [min]	15	1	3.5	7.8
Percentage of ice removed in focus area	0.5	0.9	1	1

discusses each test in detail with instrumentation, setup, results and observations. Following a discussion of each test is an estimate of the heat and mass transfer and a discussion of various parameters before the conclusion.

3. Viking Nordsafe Miriam 8.5

Two deicing tests of the Viking Norsafe Miriam 8.5 lifeboat were performed, the first on the 6th of January and the second on the 29th of March 2023. The lifeboat is 8.5 m long with a capacity for 55 people. The vessel is categorized as a fire-protected lifeboat and therefore equipped with an external sprinkler system to distribute seawater in a water film that envelopes the vessel. This water distribution system was used to test the concept of removing ice with seawater. The weather conditions, initial ice configuration, and freezing time prior to deicing differed between the tests. Predominantly, the test in January was performed on a greater initial ice thickness, lower ambient air temperature, and more time for the ice to settle before the test. The instrumentation, set-up, and procedure for performing the tests, however, were similar and the tests are therefore discussed simultaneously.

Table 3
List of equipment.

Equipment	Specification	Comment
Test Miriam January		
Salinity meter	Hanna HI98192 USP compliant EC, TDS, NACL, Resistivity Temperature meter, with electrode: HI763133.	Range TDS 0.00 to 400 g/L. Accuracy ±1% of reading.
Thermometer, measurements during deicing experiment	Fluke 54 II B thermometer	
Air probe for Fluke	Fluke 80PK-26 Tapered Temperature Probe	Accuracy ±2.2 °C, range −40 °C to 293 °C
Water probe for Fluke	Fluke 80PK-25 Piercing Temperature Probe	Accuracy ±1.1 °C, range 0 °C to 350 °C
Water pump	Biltema, BP801, nr 17–676	
Scale	Kern DS 16 K0.1 scale	
Ice thickness	Caliper	
Weather data source, ice build-up and solidification phase	The meteorological station Narvik, elevation 31 m and distance 0.9 km from the test site (Norsk klimaservicesenter, 2024)	
Test Miriam March		
Salinity meter	Hanna HI98192 USP compliant EC, TDS, NACL, Resistivity Temperature meter, with electrode: HI763133.	Range TDS 0.00 to 400 g/L. Accuracy ±1% of reading.
Thermometer, measurements during deicing experiment	Fluke 54 II B thermometer	
Air probe for Fluke	Fluke 80PK-26 Tapered Temperature Probe	Accuracy ±2.2 °C, range −40 °C to 293 °C
Water probe for Fluke	Fluke 80PK-25 Piercing Temperature Probe	Accuracy ±1.1 °C, range 0 °C to 350 °C
Water pump	Biltema, BP801, nr 17–676	
Scale	Kern DS 16 K0.1 scale	
Ice thickness	Caliper	
Weather data source, ice build-up and solidification phase	Gill MaxiMet GMX500	
Test Palfinger FF1200		
Thermometer, measurements of seawater temperature	FLUKE 51 II Thermometer and mercury thermometer	
Weather data source, ice build-up	Aanderaa Smartguard basic w/ SR10/VR22	
Weather data source, ice solidification phase	The meteorological station Straumsnes elevation 200 m approximately 10 km from the test site (Norsk klimaservicesenter, 2024)	
Weather data source, deicing test	Aanderaa Smartguard basic w/ SR10/VR22	
Salinity	The water samples were analyzed by the research institute Sintef	
Ice thickness	Caliper and Tritex Multigauge 5650-SG Surveyor Gauge	
Test floating jetty		
Thermometer, measurements during deicing experiment	Fluke 54 II B thermometer	
Air probe for Fluke	Fluke 80PK-26 Tapered Temperature Probe	Accuracy ±2.2 °C, range −40 °C to 293 °C
Water probe for Fluke	Fluke 80PK-25 Piercing Temperature Probe	Accuracy ±1.1 °C, range 0 °C to 350 °C
Salinity meter	Hanna HI98192 USP compliant EC, TDS, NACL, Resistivity Temperature meter, with electrode: HI763133.	Range TDS 0.00 to 400 g/L. Accuracy ±1% of reading.

(*continued on next page*)

Table 3 (*continued*)

Equipment	Specification	Comment
Relative humidity	TSI VelociCalc 9565-P, snr. 9565P1741007 probe 982, snr. P17370038	
Ice thickness	Folding ruler or caliper	
Weather data source, ice build-up and solidification phase	The meteorological station Straumsnes elevation 200 m and distance 6.1 km from the test site (Norsk klimaservicesenter, 2024)	

3.1. *Instrumentation and setup*

On both occasions, the lifeboat was docked at Narvik Marina, a harbor in the north of Norway. A summary of initial conditions and test conditions is given in Table 2. Ice build-up was achieved by manually spraying the topside of the vessel with seawater from a distance of approximately four meters. A hose nozzle at a widespread setting was used to spray and disperse seawater evenly across the surface. The spray was arched towards the vessel and moved parallel to the longitudinal axis, when increased amounts of run-off were observed the spray was paused for more than 5 min before continuing. The pump used to spray seawater, see Table 3, has a capacity of approximately 3.5 m^3/h, at a pressure head of 2 m. Spray was primarily added from the port side of the vessel, in both tests.

On the 4th and 5th of January, ice was built up on the vessel within the periods highlighted in Fig. 2. In Fig. 2, the air temperature, mean wind speed and relative humidity during ice build-up and until the test start are recorded with data from a meteorological station 0.9 km from the test site. No precipitation was recorded during this time (Norsk klimaservicesenter, 2024). In January the ice settled for approximately 24 h before the deicing procedure was run. The January test was discussed in the conference paper (Sæterdal et al., 2023).

Similarly, on the 29th of March the air temperature, wind speed and relative humidity were logged with 1-min intervals, see Fig. 3. The data was gathered by the Gill weather station mounted on the lifeboat, see Table 3 for the technical specification. No precipitation was recorded on the 29th of March (Norsk klimaservicesenter, 2024). The ice settled for 1,75 h prior to the test.

In both tests ice thickness was greater on the roof compared to the side of the vessel. The ice thickness was mapped at strategic locations before each test with a caliper, see Figs. 4–7. In the photo from January in Fig. 9, the measuring location can be seen, where ice was drilled to use a caliper. The average measured ice thickness on the port side of the lifeboat was 10 mm in January and 3 mm in March. Ice on the roof was added in multiple sessions days before the experiment in both experiments, and the average measured thickness was 17 mm in January and 45 mm in March on the port side of the roof. During the test in March with a portion of newly created ice, mounting the roof to do measurements compacted and altered the ice layer, therefore, only the port side of the roof was recorded, as one side could be measured without stepping onto the ice. Fig. 8 shows the vessel before deicing. From the close-up images of the ice structure on the side of the vessel, seen in Fig. 9, air entrapment in the ice is visible.

The average air temperature during the deicing test was milder in March, −3.5 °C, compared to January −9.2 °C. However, the sea surface temperature, measured 30 min before the experiment, was lower in March with 1.9 °C compared to 3.5 °C in January. Temperatures were measured with a Fluke thermometer, see Table 3. During both tests, there was no wind, waves, or precipitation, and the lifeboat was not exposed to direct sunlight. Seawater salinity was measured at 26 ppt in January and 25 ppt in March with a Hanna salinity meter, see Table 3. In addition to the measurements video and photographs were used during the experiments to document the results.

The sprinkler system on the lifeboat is run by a pump connected to the main diesel engine. Seawater is distributed through 55 nozzles connected by two parallel sprinkler rails that run the length of the vessel. According to the manufacturer, the sprinkler pump has a capacity of 80,000 l/h, without pipe, nozzle, and other resistance factors, at a 2900 rpm engine rotation speed. The flow rate of each sprinkler is not specified. The fuel consumption is given by the manufacturer to be approximately 6.42 l per hour at 2430 rpm. However, the additional fuel consumption due to running the sprinkler system should, according to the manufacturer, not be significantly different (Viking Norsafe, 2023).

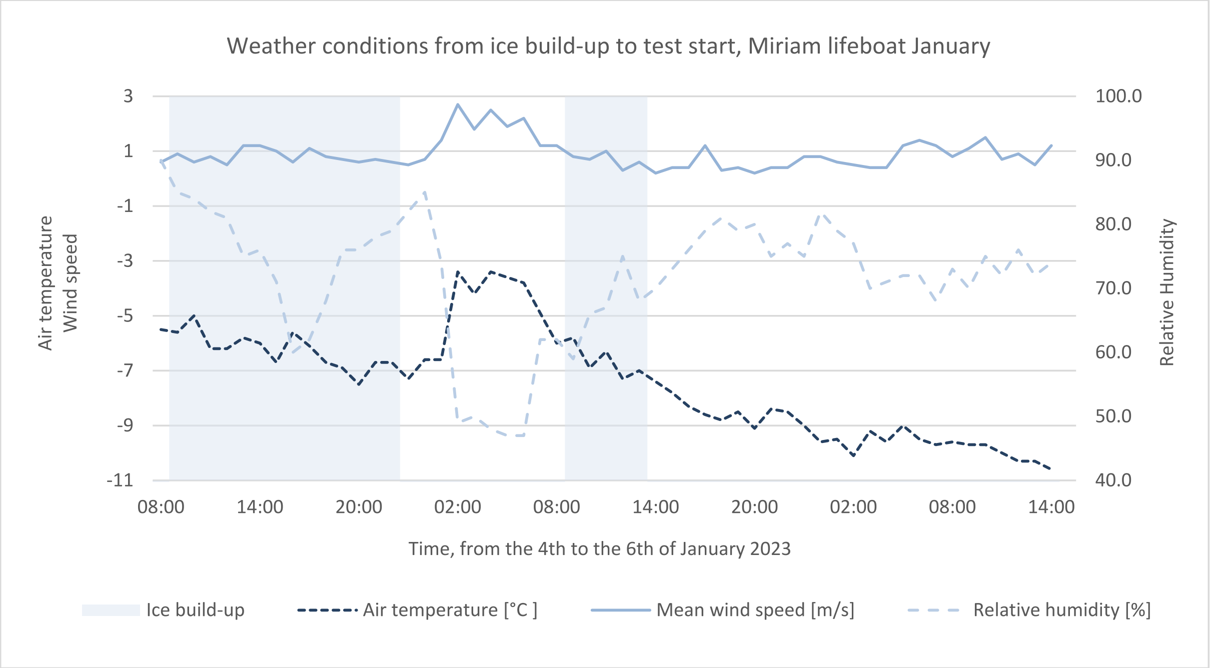

Fig. 2. Weather conditions from ice build-up to test start, Miriam lifeboat January, data from the meteorological station Narvik, elevation 31 m and distance 0.9 km from the test site (Norsk klimaservicesenter, 2024).

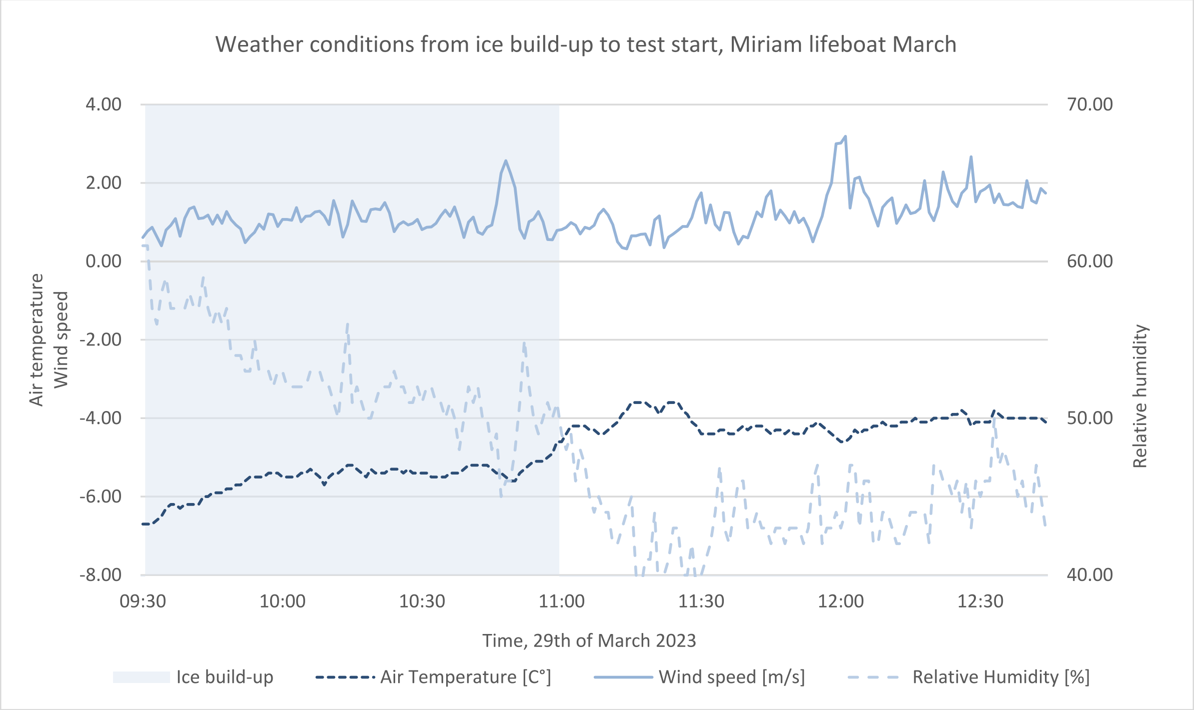

Fig. 3. Weather conditions from ice build-up to test start, Miriam lifeboat March, data from Gill weather station mounted on the vessel.

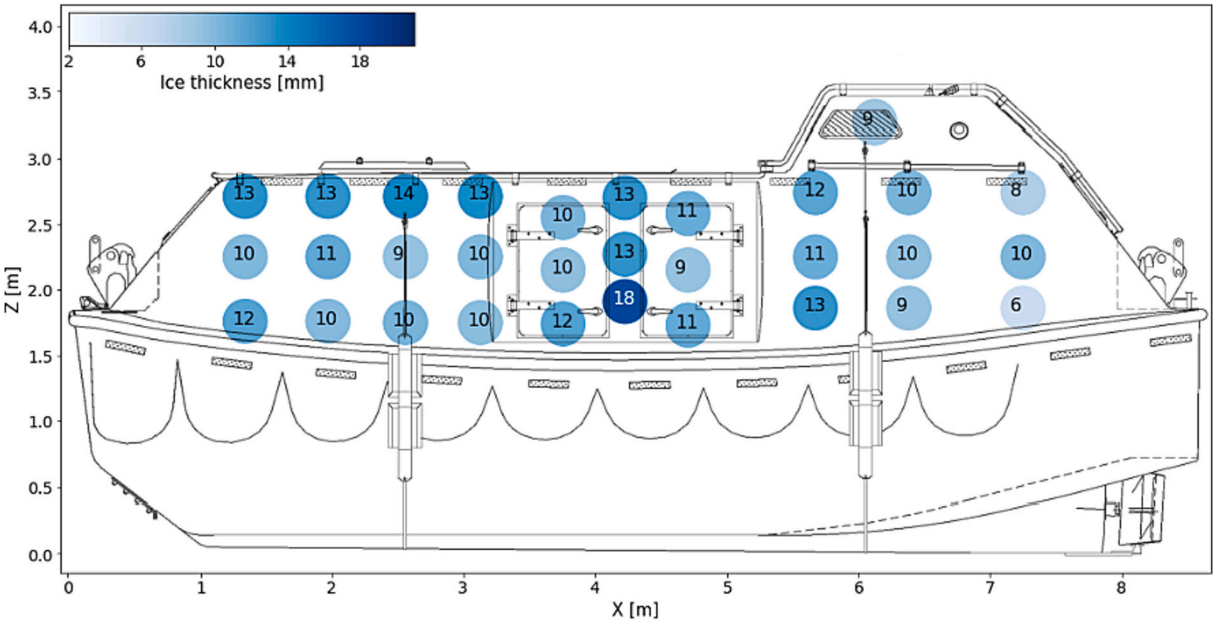

Fig. 4. Ice layer thickness port side before deicing, January.

A test was performed to measure the water flux. Waterflow from four nozzle locations was measured at 75% engine capacity. The samples were collected while timed and weighed, see Tabel 4 for scale specification. One location was tested twice with 75% engine rpm and with 50% rpm. The averaged value gives a total flow rate of 1163 kg/(h*m^2) with a standard deviation of 53. At 50% engine capacity the flow rate was reduced to 807 kg/(h*m^2).

The topside sprinkler system was run for a total of 15 min in March and 32 min in January.

3.2. Results and observations

Both tests successfully removed most of the ice accumulated at the side of the vessel. Upon starting the fire sprinkler system instantly sprayed seawater from the nozzles on both tests, despite the ice covering the pipelines. High-priority areas such as windows, air inlet, and hatches were also effectively deiced during the procedure. After the first test in January, some ice remained on the escape hatches, but it was soft, easily removed, and therefore did not block the exits. Topside equipment near the front, i.e., the attachment point for the tow rope, was not sufficiently deiced during the first test. However, the ice accumulation at this

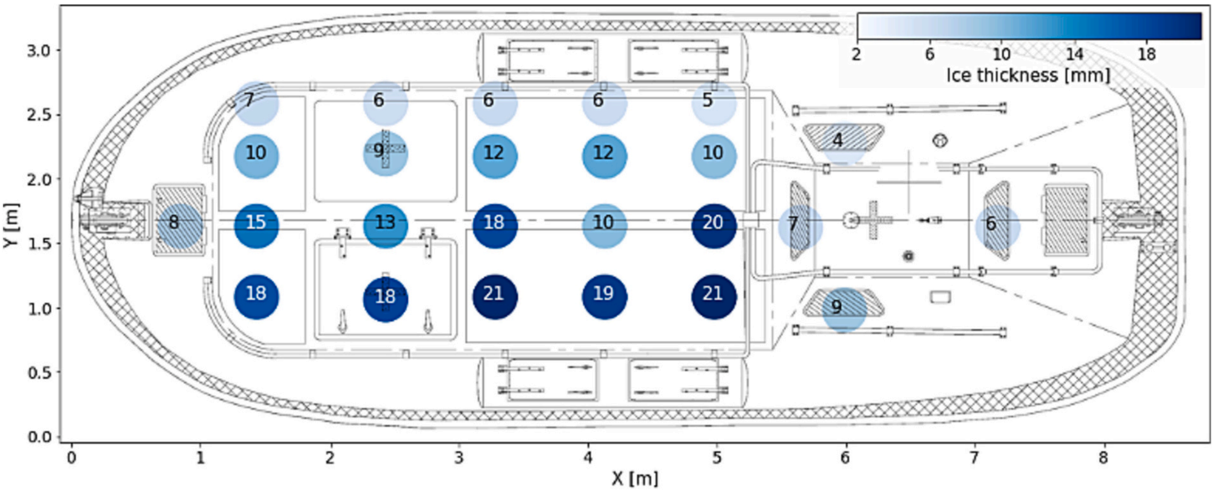

Fig. 5. Ice layer thickness on the roof before deicing, January.

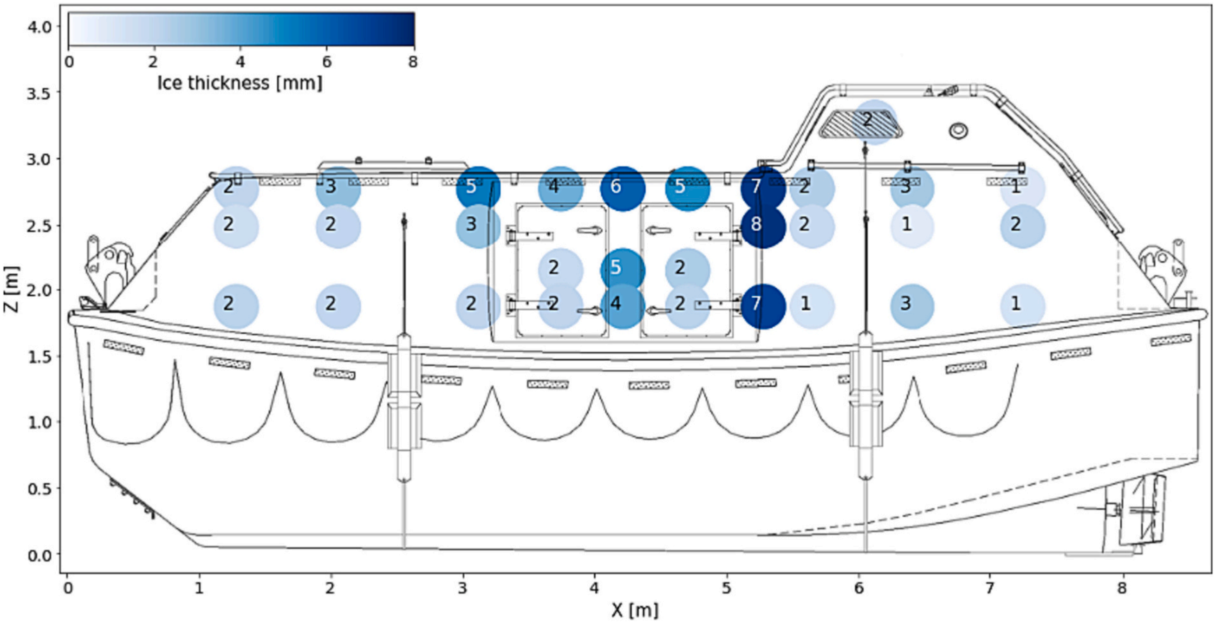

Fig. 6. Ice layer thickness port side before deicing, March.

location was not severe enough to hinder operation, due to the design.

Within 1 min most of the ice on the side of the vessel was removed during the test in March. For the settled ice with greater initial ice thickness, the process was more time-consuming, after approximately 15 min more than half of the ice was removed from the side of the lifeboat. Comparing the images captured after the deicing procedure, Fig. 10, and video from the deicing procedures, we suspect a partially blocked nozzle during the test in January located on the port side foremost on top of the steering tower. The blockage could not be detected from the footage, but the lack of deicing and pattern of the adjacent deiced areas is a strong indication, as well as the observed water distribution during the second test.

On the roof, the surface is horizontal with minimum help of gravity for water distribution and ice removal. In addition, the ice thickness was greater on the roof compared to the sides of the vessel for both tests. Consequently, the sprinkler water distribution system was not sufficient to fully remove the ice. In January, with an average initial ice thickness of 17 mm on the port side of the roof, the remaining ice layer was reduced in thickness, and locally deiced areas occurred, see Fig. 12. The remaining ice was easy to remove manually. In March, with an average initial ice thickness of 45 mm, measured ice thickness after the test did not show a reduced ice layer, see Fig. 11. In some areas, the ice thickness increased. Observations after the test, however, revealed that the ice structure was severely compromised. In zones directly in the path of the nozzle spray, cavities had formed beneath the ice layer. In some areas, the ice layer was easily compressed when a load was applied on the ice. See the ice on the roof after the test in Fig. 12. The test duration time was halved in March compared to January; if the test had been run for a similar duration there might have been a reduced ice thickness. Estimates concerning heat and mass transfer are given in Tables 4 and 5.

After the deicing tests, a thin water layer solidified on the surface, but the thickness was insignificant. No refreezing of the pipelines was observed between tests, which indicates sufficient drainage of the system.

4. Palfinger Harding FF1200

In January 2018 Professor Sundsbø performed the first deicing test of

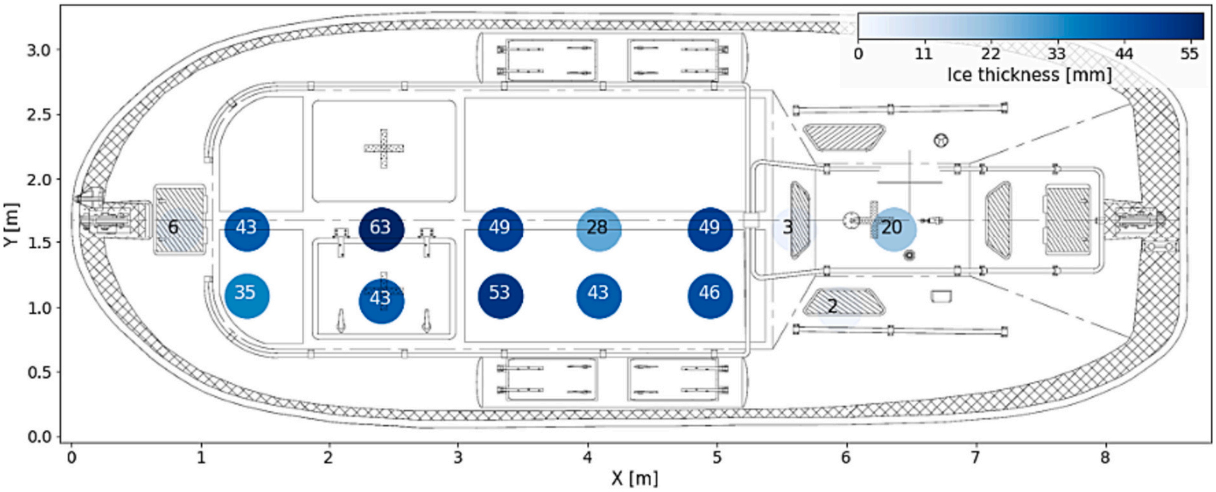

Fig. 7. Ice layer thickness on the roof before deicing, March.

Fig. 8. Ice layer on the Miriam lifeboat prior to tests, March (left) and January (right).

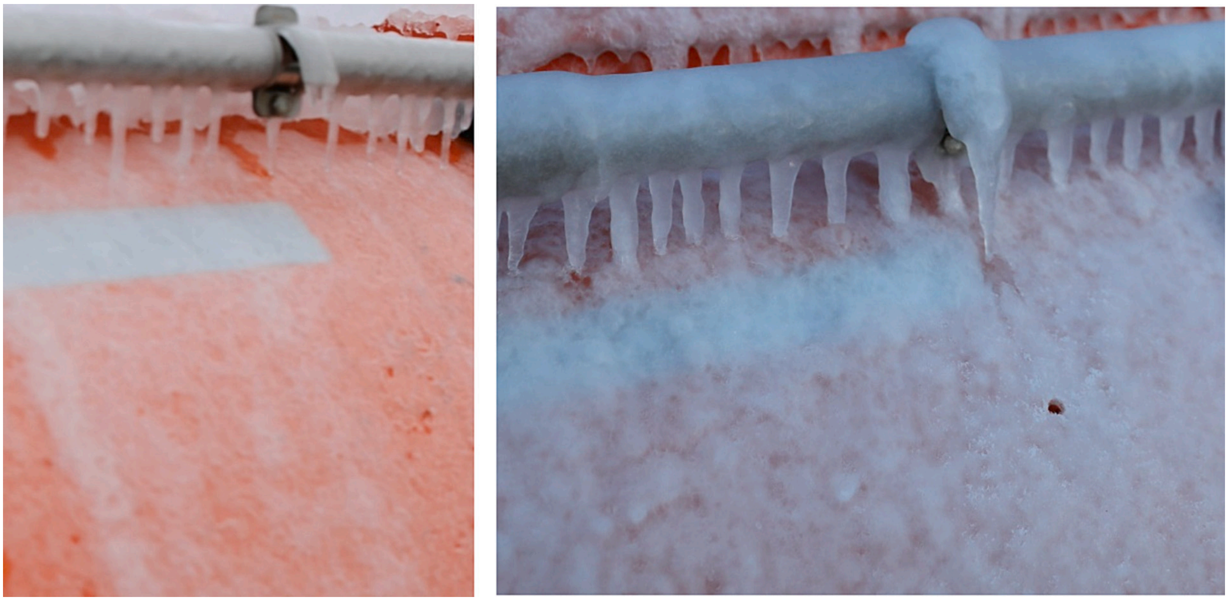

Fig. 9. Close-up of the ice layer on the Miriam lifeboat prior to tests, March (left) and January (right).

Table 4
Results: deicing rates and percentage removed ice based on incoming water flux.

System	External sprinkler system, Miriam January	External sprinkler system, Miriam March	External sprinkler system, Palfinger FF1200	Fire hose, service vessel Narvik Harbor
Deicing rate [kg/(m^2*h)]	18	147	78	384
Average water flux [kg/(h*m^2)]	878	1163	852	3695
Percentage of removed ice based on applied water flux	2%	13%	9%	10%

a lifeboat. The test was performed during an R&D project with The Arctic University of Norway, Eni Norge and Palfinger Marine Safety, with support from Narvik Harbor Services. The aim of the project was to address potential icing problems and other winterization issues on the FF1200 Lifeboat (Sundsbø and Jacobsen, 2018). The vessel is a 16.7 m long free-fall lifeboat with a capacity for 70 people designed according to DNVGL-ST-E406/ NORSOK R-002 and SOLAS standards. Sea-spray ice accumulation and other findings were documented and recorded. The following day a deicing test was performed by utilizing the topside fire-sprinkler system, and data from this test is discussed in this paper.

4.1. Instrumentation and setup

Metocean conditions during the sea-spray icing test were measured by two Aanderaa weather stations, see Table 3, one on the lifeboat and the second on the support vessel. In addition, a rider buoy was launched to measure wave height. The conditions during ice build-up in the Ofotfjord were an average air temperature of −9.2 °C, mean wind speed of 9.7 m/s, seawater temperature of 4.0 °C, and 1.3 to 1.5 m wave heights. The metocean conditions correspond to fast icing, between 10 and 30 mm/h, according to the guidelines (ISO 19906, 2019). In the sea-spray icing test ice was accumulated on the lifeboat within the period of 1.5 h. Flushing and consequently ice removal was observed in certain areas when using provocative maneuvers to increase the frequency of sea-spray. Fig. 13 illustrates the initial ice layer distribution on the vessel before deicing, and Fig. 20 shows a close-up of the ice and sprinkler system.

The ice settled for 21 h before the deicing test. Fig. 14, show the metrological conditions when the ice settled with the average air temperature, wind speed and relative humidity with data from a meteorological station Straumsnes approximately 10 km from the test site. No precipitation was recorded during this time (Norsk klimaservicesenter, 2024).

During the deicing test the following conditions were recorded; −8.7 °C air temperature, no wind, 3.5 °C sea surface temperature, and seawater salinity of 31 ppt. The salinity was measured by the research institute Sintef, and the meteorological data was gathered from the weather station mounted on the lifeboat. The proceedings were recorded with GoPro cameras for documentation and later evaluation. The deicing procedure was run for 16 min, of which the engine ran at 1600 rpm the first minute, and 2500 rpm for the remainder of the test. The fuel

Fig. 10. Portside after the deicing procedure in March (left) and January (right).

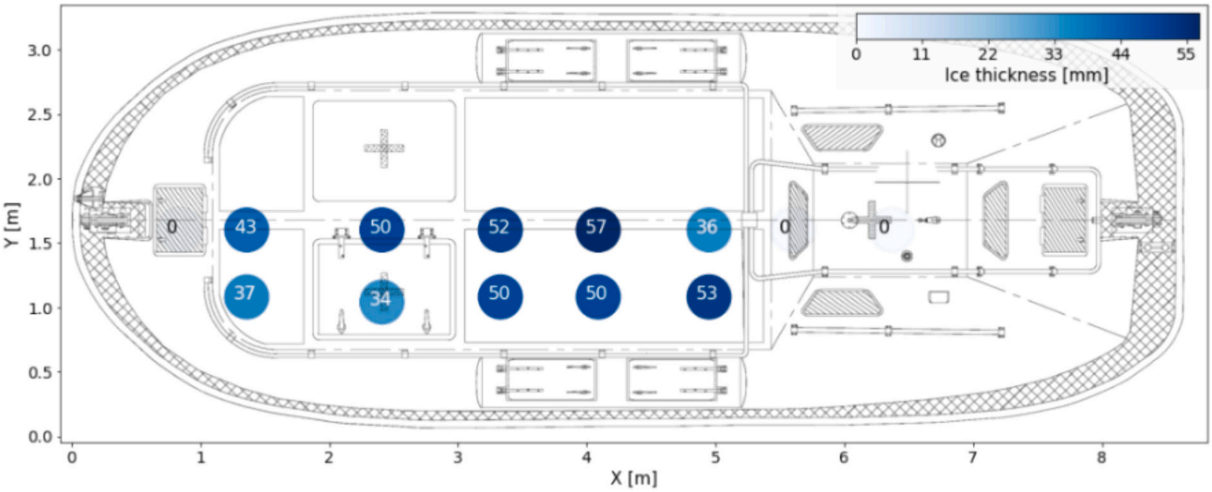

Fig. 11. Ice thickness measurements on the roof of the Miriam lifeboat after the deicing test in March.

Fig. 12. Ice on the roof after deicing test Miriam lifeboat, March (left) and January (right).

Table 5
Results: heat capacity.

System	External sprinkler system, Miriam January	External sprinkler system, Miriam March	External sprinkler system, Palfinger FF1200	Fire hose, service vessel Narvik Harbor
Sum specific and latent heat flux in ice removed [kJ/(h*m2)]	6399	50,112	27,346	130,538
Percentage specific heat flux in ice removed	4.8%	1.5%	4.5%	1.5%
Specific heat flux of applied seawater [kJ/(h*m^2)]	15,385	13,130	14,926	80,555
Applied energy/ Energy to melt the ice	2.40	0.26	0.55	0.62
Energy input divided by removed ice [kJ/kg]	845	89	191	210

consumption given by the manufacturer for the vessel in calm water is 9 and 51 l/h for a rpm of 1500 and 2650, respectively. According to the manufacturer, the added fuel consumption for running the sprinkler system when the vessel is sailing is negligible. The flow rate has been measured to 1920 l per meter when the engine is run at 1500 rpm (Palfinger, 2023). Distributed over the topside surface area this translates to 511 l per square meter per hour. Linearly scaled to an engine rpm of 2500 the flow rate is 852 l per square meter per hour. A summary of initial conditions and test conditions is given in Table 2.

4.2. Results and observations

The test was successful and no ice remained on the vessel after the test. Even though the procedure eventually removed the ice, a challenge was uncovered during the test. At the start of the test sprinkler nozzles in front of the steering tower were blocked by ice, see Fig. 15. Within 2 min most of the ice aft of the steering tower was removed, but the front sprinklers remained frozen. Gradually the nozzles thawed from the steering tower towards the bow and subsequent deicing occurred almost instantly. The test was run until all sprinklers were operational. Estimates concerning heat and mass transfer are given in Tables 4 and 5.

After the experiment, the sprinkler system was drained and reactivated to investigate potential refreezing issues. A 75-min break between draining the pipelines and restarting was used, and the result was a fully operational sprinkler system where all nozzles delivered water at the restart. The prompt delivery of water indicates that the system was successfully drained before the restart.

5. Sildvik harbor

At Ytter-Sildvik, in the North of Norway, the harbor is exposed to sea-spray icing because of its location and local weather conditions. After a period of low temperatures and strong wind, peaking at −13 °C and 25 m/s gusts, respectively, the floating jetty had accumulated a substantial amount of ice from sea-spray. The direction of spray and ice build-up at primarily one side of the dock challenged the structure's stability. With cooperation from Narvik Harbor Services, an attempt was undertaken to deice the harbor with the fire hose aboard their vessel.

5.1. Instrumentation and setup

During the field test an air temperature of −3.5 °C and relative humidity of 66% was recorded approximately 1 m above the sea surface. Initial ice thicknesses measured between 30 and 220 mm. The seawater and ice salinity were measured at 26 ppt and 10 ppt respectively, and the sea surface temperature was 4.6 °C. In addition to measurements, observations supported by pictures, thermographic pictures, and videos were used to investigate ice and water distribution.

The majority of the ice on the harbor had accumulated and settled days before the test. Fig. 16 shows the weather conditions from the closest meteorological station, 6.1 km from the location, with mean wind speed, air temperature and relative humidity in the days leading up to the field test. On the 21st of January, the wind speed increased and the next day the ambient air temperature dropped below −10 °C. The period of strong eastern wind persisted until the 23rd of January and facilitated ice build-up. The threshold where fast icing can be expected, Table 1 (ISO, 2019), was reached for a total of 27 h in the period. The harbor authorities had previously removed ice on a portion of the harbor, the outline of this area can be seen in Fig. 17, and the ice thickness in this area averaged 55 mm, and it is assumed that ice on the remainder of the area partially predated the timeframe in Fig. 16.

The ice settled for several days until the deicing test on the 28th of January, during this period the ambient air temperature was below −10 °C until a rise in temperature to above −10 °C around the 26th of January. Due to the elevation of the meteorological station, Straumsnes, at 200 m, the ambient air temperature is slightly lower than the temperature at the test site. The air temperature during the test was measured at −3.5 °C, one degree higher than the −4.5 °C recorded by the meteorological station. Some icing could have occurred in the periods of slow icing. The recorded precipitation during the period was 0.1 mm in total.

The integrated firehose, powered by the vessel engine, sprayed seawater at the accumulated ice. The deicing procedure was carried out for 31 min, with a step increase of engine power from 1200 to 2000 rpm.

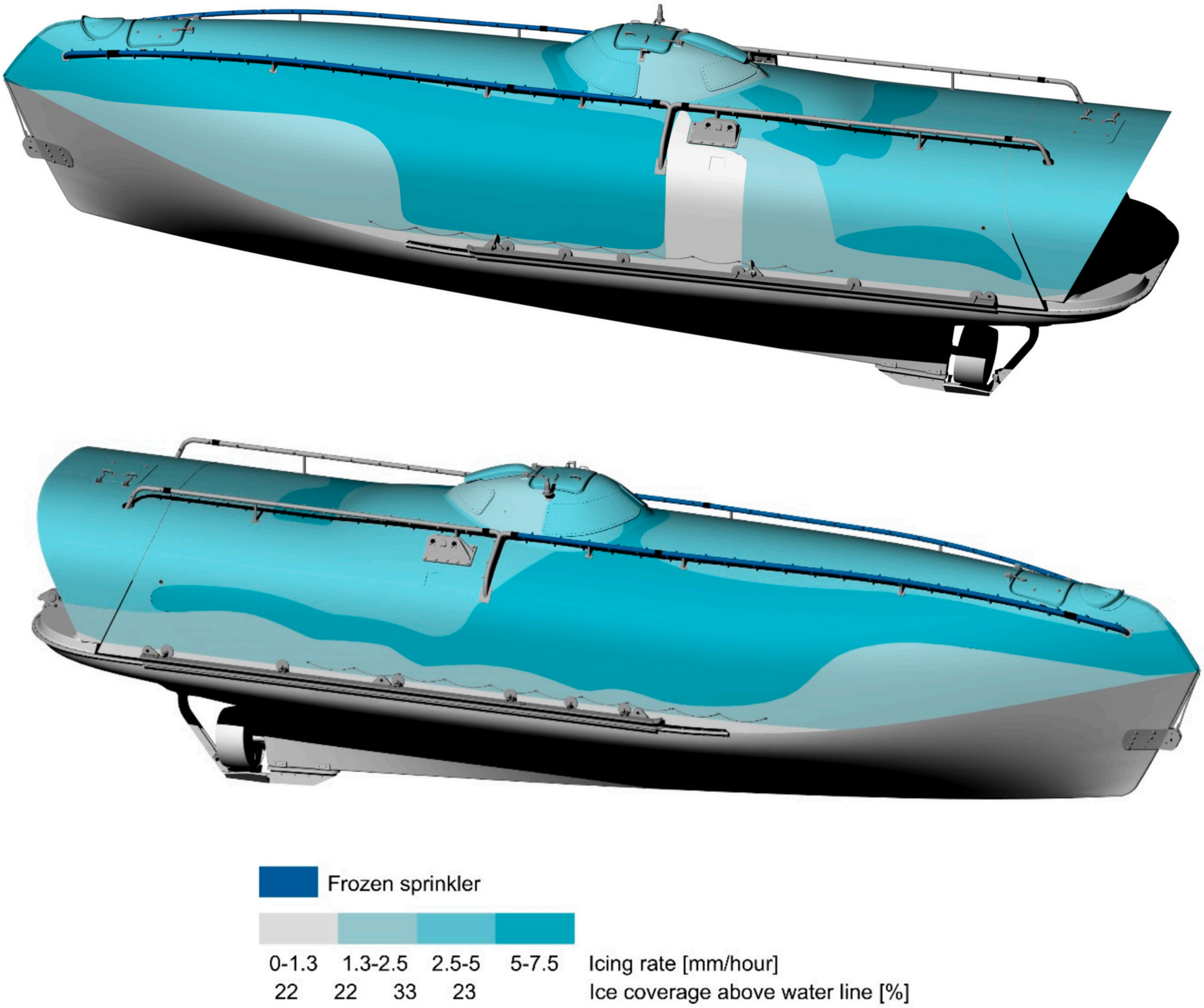

Fig. 13. Icing rate distribution Palfinger FF1200 lifeboat before deicing procedure (Sundsbø and Jacobsen, 2018).

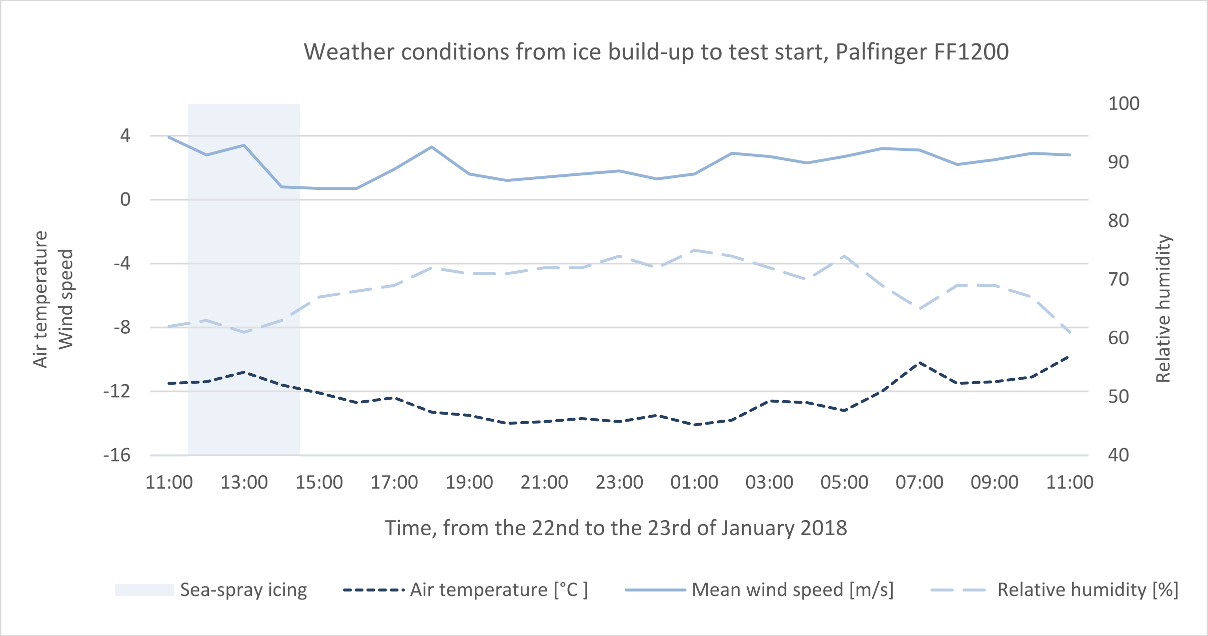

Fig. 14. Weather conditions from ice build-up to test start, Palfinger FF1200, data from the meteorological station Straumsnes approximately 10 km from the test site.

Fig. 15. Deicing of the Palfinger FF1200 lifeboat (Sundsbø and Jacobsen, 2018).

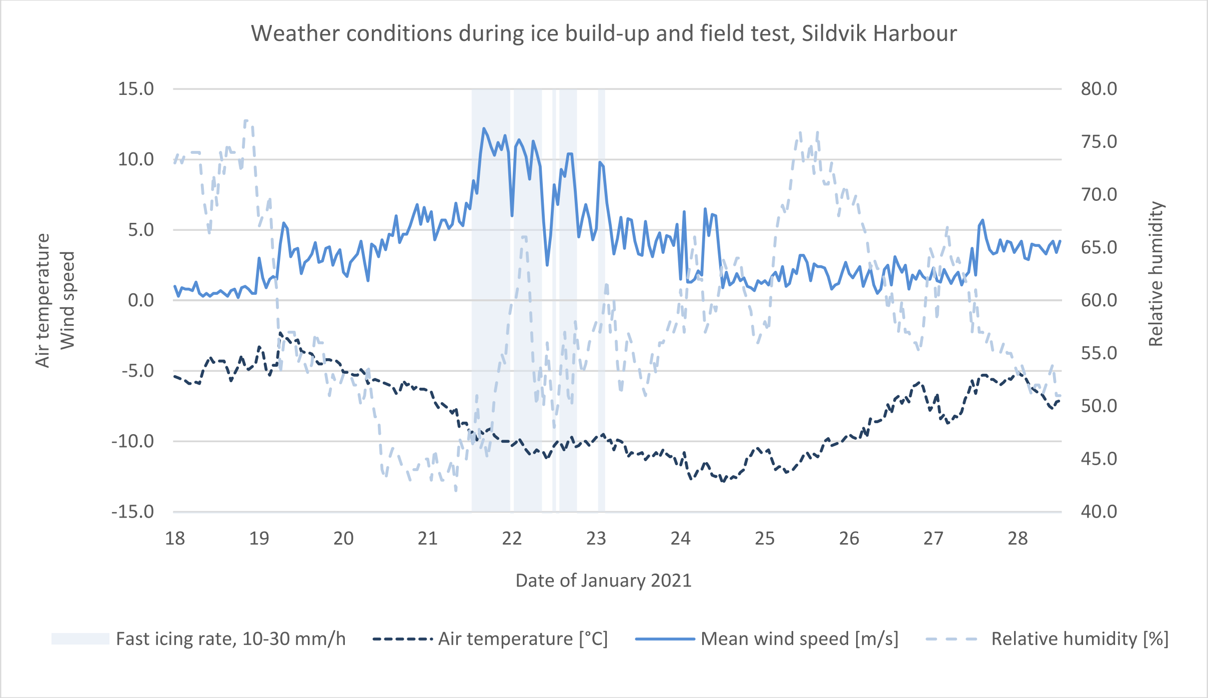

Fig. 16. Weather conditions preceding the field test at Sildvik Harbor, weather data from the meteorological station Straumsnes elevation 200 m and distance 6.1 km from the test site (Norsk klimaservicesenter, 2024). The shaded area on the graph shows intervals where the weather conditions corresponded to a prediction of a fast icing rate (ISO, 2019), the remainder of the period the weather conditions corresponded to a prediction of slow icing with <10 mm/h.

5.2. Results and observations

The main efforts for deicing were concentrated at the Southwest half of the dock, with the aim of reducing the ice load on this side to stabilize the structure. The seawater was sprayed at a slow pace across the 20-m-long edge, back and forth. About halfway through the procedure, the deicing effort was directed towards the part of the dock where the effect was most visible. Fig. 17 shows the dock before and after the experiment. Ice was removed due to the thermal capacity of the water but also broken apart by the impact of the concentrated jet from the fire hose. When aimed at the separation line between the substrate and ice edge, the water jet effectively broke apart pieces of ice, see Fig. 18. For approximately 8 min the spray was focused on the eventually deiced area, and the first 2 min had reduced engine power. The deiced area measured approximately 11 m^2, resulting in an ice removal rate of roughly 4130 kg/h, given an assumed ice density of 0.91 Mg/m^3 (Timco

Fig. 17. The pictures show the dock at arrival and close to the end of the experiment.

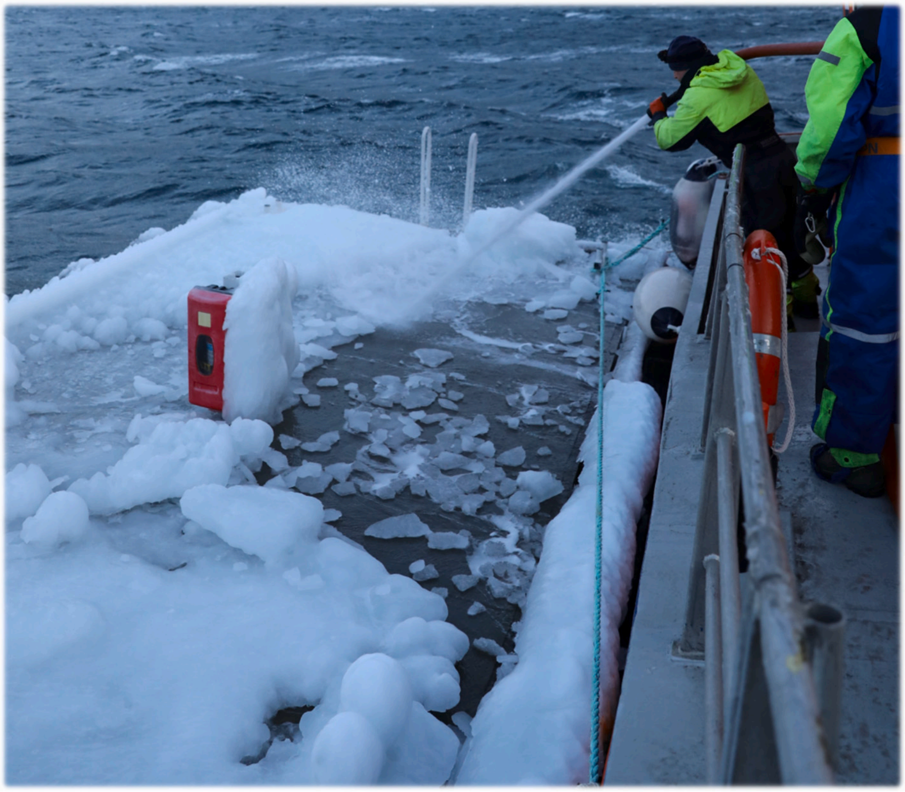

Fig. 18. Ice break-up when removing ice with a fire hose at full capacity.

and Frederking, 1996) and ice thickness of 55 mm. The estimated ice removal rate does not reflect the melting capacity as success was defined when ice was sufficiently broken apart to be efficiently removed. A rough estimate of the overall initial ice load on the dock gives a total ice load of >10,000 kg.

The experiment revealed limitations to the use of seawater as a deicing tool. Solid ice thicker than approximately 5–6 cm would be too time-consuming to deice under the given conditions. Contributing to the challenging situation was the horizontal surface enclosed by a toe board, or heightened edge along the dock, which discouraged removing ice by shifting it off the platform. Applying seawater on the dock made manual removal easier. The deicing procedure weakened the ice structure, and a water layer developed between the ice and substrate, consequently the ice was easy to break away from equipment located on the dock. With thick ice layers on horizontal surfaces, deicing with seawater is more feasible directed towards high-priority equipment and smaller areas. Estimates concerning heat and mass transfer are given in Tables 4 and 5.

6. Estimate of heat and mass transfer

Ice removal was monitored and clocked from video recordings over selected areas from the previously described experiments, see Table 2. On the Miriam lifeboat, the inclined port side surface from the hatches towards the bow was selected. On the Palfinger vessel, the inclined surface at the port side of the bow was observed, and on the harbor jetty, the area of initial lower ice thickness was clocked to determine the deicing rate. The average water flux was compiled from the water flux estimations at specific engine capacities and rotational speed. For instance, in the January testing of the Miriam lifeboat, the engine worked at 50% capacity for most of the time, and the average water flux was consequently lower compared to the test from March. The results, in Table 4, show that significant amounts of seawater were used to remove ice, a ratio of 1 to 10 per kilogram of ice removed and seawater applied respectively. The exception was the deicing of the Miriam lifeboat in January. Ice removed only weighed 2.1% of the added water flux.

An estimation of the specific heat and latent heat needed to melt the ice is compared to the specific heat potential in the applied water. Many factors can influence the heat balance, such as kinetic energy, convection and conduction etc., but the specific and latent heat is assumed to be the greatest contributing factors. The computation assumes that:

- The ice temperature, T_i, is equal to the ambient air temperature.
- The freezing temperature of seawater, T_f, –1.0 °C, due to reduced salinity in the ice and seawater.
- The density of ice is given the value 910 kg/m^3.
- Specific heat of ice, C_i: 0.49 kcal/(kg*°C).
- Specific heat of seawater, C_w 0.93 kcal/(kg*°C).
- 1 kcal = 4186 J.
- Latent heat of ice, L_f 80 kcal/kg.

The greatest unknown factors are run-off with potential unused energy, mechanically removed ice, and ice removed without melting, for example, removed from the surface in patches of ice or brine. These factors are particularly relevant for the inclined surfaces on the lifeboats. The variables are given, when possible, in units that represent the time duration of 1 h and an area equal to 1 m squared. The energy required to melt ice is computed by the equation:

$$Q_{ice} = m_i{}^*L_f + m_i{}^*C_i\left(T_i - T_f\right)$$

The sensible heat flux of the applied seawater is computed by the following equation:

$$Q_{seawater} = m_w{}^*C_w\left(T_w - T_f\right)$$

The results are shown in Table 5 with the ratio of applied energy over energy for phase change and the energy input per kilogram of removed ice. Theoretically, 334 kJ is required to melt 1 k of freshwater ice, except for the January test, all systems used less energy to remove ice.

7. Discussion

7.1. Effect of ambient air temperature

The distance between a water distribution system outlet (nozzle) and the target area for deicing is expected to be short, consequently, the ambient air temperature is less critical. Low ambient air temperatures are concerning when considering adjacent zones where icing from airborne particles could increase, and if the distance for run-off is sufficient to cool down the deicing liquid and cause icing. During the tests with the lowest ambient air temperature, −9.2 °C, some ice accumulation occurred in low-flux areas (Sæterdal et al., 2023), but freezing in the run-off pathways was not observed. If the deicing procedure is initiated when the ice is settled, the ice can have the same low temperature as the ambient air.

7.2. Effect of seawater temperature

The lowest seawater temperature tested was 1.9 °C, and no complication or lack of deicing capabilities was observed due to the low temperature. However, increased seawater temperature is expected to enhance the deicing rate, and an investigation of the cost vs. reward of a minor temperature increase should be investigated.

7.3. Ice layer

Ice can be melted, the time and flow rate required are the key factors for deicing with seawater. Deicing ice thicknesses from 3 to 220 mm have been evaluated in this paper. Even with the most powerful distribution system, the firehose, deicing was not considered efficient on a horizontal surface for ice thicknesses above 50–60 mm. During the full-scale tests, ice thicknesses below approximately 4 mm were removed within minutes provided the distribution system was fully operational. The time needed to deice ice thicknesses above this range was highly dependent on the distribution system. Areas in direct contact with spray from the nozzles, with an initial ice thickness of about 10 mm, were generally deiced within 5 min. Due to the different distribution methods and surrounding conditions, the results cannot be compared, but give an indication.

The experiments removed ice created by sea-spray and ice build-up applied manually with a hose. The full-scale tests successfully deiced both settled and newly formed ice. When sailing in sea-spray icing conditions, it is reasonable to expect that efforts towards removing ice would start shortly after ice accumulation. Considerations such as visibility or compromised functionality could dictate the required deicing frequency. Ice removal will be easier if the deicing commences before the phase change from sea-spray droplets to solid ice has been completed.

7.4. Seawater distribution systems for deicing

All vessel deicing distribution systems tested were successful at deicing. The tested vessels were lifeboats with external fire sprinkler systems. In accordance with the regulation, a fire-protected lifeboat shall be capable of sustaining continuous oil fire that envelops the lifeboat for a period of no <8 min (IMO, 1998), which includes a water film covering the exterior of the vessel. The fire sprinklers provided a convenient seawater distribution system to test full-scale deicing of vessels in general, but the systems can potentially be designed to provide a dual purpose.

In the discussed cases, the water distribution systems were not originally designed for deicing. This is particularly evident on the Miriam lifeboat roof. On the vessel, a total of 8 nozzles were directed towards the roof, and some had an angle of spread that prevented the water from reaching the roof. On the Palfinger Harding lifeboat, the distance between nozzles was shorter, and deicing was more efficient. Other considerations and differences between the hull shape, surface roughness, and initial ice thickness need to be addressed when determining the relative success of the systems for deicing purposes. An evenly distributed water flux is important to prevent the liquid from gathering and running off the structures in pathways that do not contribute to deicing, as seen on the Miriam lifeboat. Optimal design for deicing with seawater should also utilize the surface design to harvest the full potential of run-off. On a convex shape like the lifeboats, distribution across the longitudinal centerline of the roof could probably deice the entire boat due to run-off.

During the exercises, run-off drained easily from the vessels. The pathways and potential water accumulation areas, such as concave surfaces, deck equipment, etc., need to be evaluated at the design stage. Refreezing of lingering liquid after deicing may occur. The ice layer thickness observed after deicing procedures was minor. As a precaution, however, hatches and doors should be opened after deicing to prevent freezing.

The sprinkler pipes used for deicing were quickly deiced due to heat transfer by conduction. This type of distribution of sea water could be used to advantage by for instance incorporating the distribution channels into railings or other elements of ship design. The windows were efficiently deiced during all lifeboat tests. On both vessels, several nozzles were directed towards the windows, and this is one example of how targeted delivery can be directed towards a specific high-priority zone. Such considerations should be included in the planning phase when designing water distribution systems for deicing.

Deicing with a fire hose showed how high pressure can add efficiency to the ice removal process. The added pressure combined with the flexibility of a hand-operated device allowed water flow to break up the ice layer at the edge from underneath. However, it is not plausible to deice large areas with a handheld hose, nor that each nozzle will have a flow rate equal to that of a firehose.

If a deicing procedure is run during sailing in sea-spray icing conditions, the contribution from the seawater distribution system could convert the potential ice accumulation into added water flux for the deicing effort. This method could expand the thermally limited accretion zone, as described by Ryerson (2008). With the added supply of water, deicing in weather conditions with icing rates >30 mm/h should be possible. The described icing rate corresponds to very fast icing conditions in the guidelines for sea-spray icing rates in ISO 19906 (ISO, 2019). This, of course, must be tested with a system designed for deicing.

Adding water flux could also be achieved by deliberate maneuvers to increase sea-spray. If the vessel is suited for such maneuvering, this method could be part of the operating procedure to prevent and remove ice.

7.5. Nozzle design

The nozzle design is an important element of the seawater distribution system. A fully operational system is essential for vessel safety. The two tested lifeboats have different solutions for the nozzle design, as can be seen in Figs. 19 and 20. On the Miriam lifeboat holes in the distribution pipeline allow water to exit, and a metal sheet deflects and spreads the water on the vessel's surface. The angle of this shield greatly affected the water distribution, and the flexible sheet was easy to distort reducing its performance. During the icing phase, the metal sheet largely protected the pipeline from clogging. During the experiments on the Miriam lifeboat the seawater was applied manually, and the result could have been less favorable with ice created from sea-spray due mainly to the lateral wind forces. The FF1200 Lifeboat had an ice layer created by sea-spray during operational conditions, and some of the extruded nozzles clogged as a layer of ice encapsulated the nozzles. Once the nozzles thawed the water was finely distributed, as can be seen in Fig. 15.

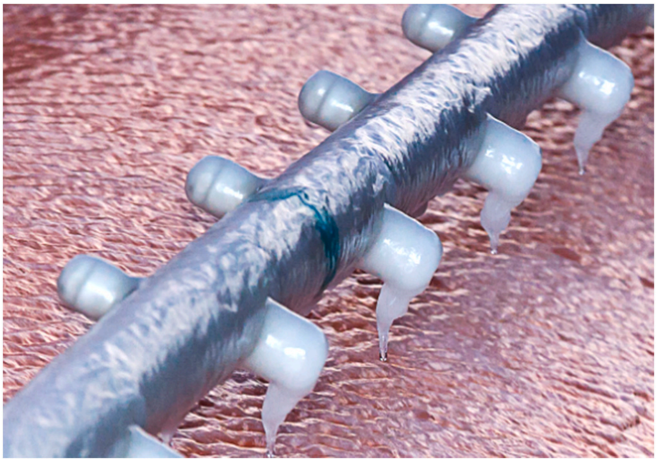

Fig. 20. The Palfinger FF1200 lifeboat sprinkler nozzles before deicing (Sundsbø and Jacobsen, 2018).

8. Conclusions and recommendations

Seawater is abundant and the application of seawater has no negative environmental impact. The resource could be used to combat ice accretion on vessels, offshore installations, and exposed harbors sections. This work started in 2018 during a full-scale sea-spray icing measurement campaign on a FF1200 lifeboat where one of the objectives was to test whether the existing sprinkler system could be used for deicing and the potential effectiveness by using the system as such. The lifeboat was successfully deiced, despite that only the nozzles aft the tower was open prior to the test and that the ice had hardened on the canopy during the night. The sprinkler nozzles and piping drained efficiently after test de-icing test and was not frozen or clogged by ice in compliance with acceptance criteria. This test alone shows a promising potential for deicing in waters with plus degrees sea temperatures. Overall, the results gathered from four full-scale tests indicate that deicing with seawater has potential. All tests using sprinkler distribution systems successfully removed ice. Sprinkling or flushing is particularly efficient at flushing off relatively thin ice on inclined surfaces with a limited amount of deck equipment or details. The ice is removed in a

Fig. 19. Sprinkler nozzles before and after deicing the Miriam lifeboat.

combination between melting and mechanical flushing from the nozzles. Most efficient ice removal is in areas where the incoming water reduces the ice attachment to the surface by partly melting or loosening sections of ice that slides or flushes away. Deicing through pure melting seems inefficient and there is certainly a balance between energy needed for mechanical flushing and energy used for melting of the ice.

Generally, deicing under the tested conditions was achieved with a ratio of 1 to 10, where the removal of 1 kg of ice required 10 kg of flushing seawater. When investigating the heat balance, however, it is evident that the specific heat of seawater applied was greater than the specific and latent heat of ice combined. This indicates that a portion of the ice was removed from the vessel without thawing. The observed speed of the water film and amount of run-off also advocate that less of the seawater's specific heat was utilized for melting. Increased ice thicknesses proved challenging to remove, the seawater did not easily penetrate the ice. Initial ice thicknesses of 10 mm had a percentage of removed ice based on applied water flux of only 2%. With a fire hose, an ice thickness of approximately 55 mm was removed, but greater ice thicknesses were deemed too time-consuming to deice with the method.

The energy consumption to run the water pumps was not recorded, but as the pump is connected to the main engine of the vessels the additional energy to run the pump compared to the fuel consumption for sailing the vessel was expressed as negligible and not significantly different by the manufacturers (Viking Nordsafe, 2023; Palfinger, 2023). As a comparison to other methods the 100-m-long icebreaking polar research vessel, FF Kronprins Haakon is equipped with heating cables. The chief officer on board shared that the vessel can easily use 3000 kWh to run the electrical anti-and deicing system, and assesses whether to power up an additional generator when using the system (Mork, 2023).

An optimal design of a seawater distribution and flushing system is essential for the success of deicing or anti-icing with seawater. Within the limitations of the existing systems, the paper has shown the potential for developing such solutions. The method is applicable for surfaces where run-off is efficient and not restricted. An evaluation of hull design and flow paths needs to be included during the planning phase. Surface design adaptations and targeted delivery could enhance the deicing efficiency for high-priority zones from natural sea-spray and added flow. An optimal frequency of deicing can be overruled by fulfilling criteria such as visibility. Alternatively, when such challenges are acknowledged, localized deicing or other deicing methods are an option. Deicing intervals should be recommended and implemented in safety procedures.

During sea-spray icing conditions an increase in spray flux through an increase of vessel speed, provocative maneuvers or wind-wave characteristics may remove ice or hinder further ice build-up. Deicing of vessels using sprinklers or nozzle systems seems suitable in situations where an increase in the same sea-spray flux that builds up ice, is removing or hindering further build-up. The runoff must be able to escape without forming new ice. These are conditions most likely to occur on small up to medium-sized vessels, or structures.

Deicing with lifeboat sprinklers is tested successfully with plus-degree surface seawater temperatures from 1.9 to 3.5 °C and air temperatures from −3.5 to −9.2 °C. These are winter offshore temperatures that is likely to occur at larger parts of the Barents Sea (Saipem Energy Services, 2014; Equinor, 2022; Statoil, 2016) and along the Norwegian coast.

During wind and extremely low temperatures in sea, air and on the vessel surface, deicing using seawater may lead to more ice build-up, even if the flushing water is above the freezing temperature of seawater. This method has certainly its limitations and further work should focus on finding the safe range of metocean conditions to apply this method and design of an effective water distribution system adapted to the specific vessel. Full-scale testing is comprehensive and challenging. This work represents a valuable first step and concept evaluation for developing efficient and environmentally sound methods for deicing. Time and energy needed for deicing are crucial factors in an emergency situation and safe deicing routines must be developed for various applications.

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CRediT authorship contribution statement

Ane Sæterdal: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Per-Arne Sundsbø:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ane Saeterdal reports equipment, drugs, or supplies was provided by Viking Norsafe life-saving equipment Norway AS, provided lifeboat for testing. Ane Saeterdal reports equipment, drugs, or supplies was provided by ENI Norge AS, provided lifeboat for testing.

Data availability

Data will be made available on request.

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