Marine icing
A probabilistic icing model from sea generated spray

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MASTER OF SCIENCE THESIS

For the degree of Master of Science in Offshore and Dredging Engineering at Delft University of Technology

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Due to signs of declining ice coverage of the Arctic seas in recent years, it is expected there will be more open water in these areas. The operations of ships in these Arctic areas are delayed and endangered by icing, which is caused by sea spray that freezes onto the ship due to sub-zero air temperatures. Possible risks due to marine icing are blocking of operational equipment, slippery decks, ladders and rails, blocking of evacuation and firefighting equipment, and an influence on the stability of the ship. To secure safe shipping operations, it is important to correctly predict icing due to sea spray.

Earlier work done by MARIN on marine spray has resulted in the first stage of the SHIPICE model. This first stage was a probabilistic model for volumes of spray, and the break-up in droplets, rising above the freeboard. During this graduation project, the second stage of the SHIPICE model is developed, which considers the ballistic and thermodynamic process of sea spray droplets while flying through the air and subsequently impact and freeze to the ship. The aim of this research is thus, the further development of a probabilistic icing model, named SHIPICE.

Depending on the considered sea state and ships velocity, the size and velocity of the sea spray droplets may vary significantly. In this project, the different droplet sizes and velocities are incorporated into an icing model for the first time. To this purpose, depending on the droplet sizes and starting position, first the trajectory of all droplets is considered separately to determine the location where the droplets hit the ship, which is divided in 42 areas: the 21 stations of the ship on respectively starboard and port side. Then, the ice thickness and ice growth per area is calculated based on the spray flux per area. The intensity distribution on the deck was then compared with model tests in regular waves. Note that, from the total volume of spray rising above the ships deck, only a small amount (approximately 1%) will land on the ship, where the smaller droplets are more influenced by the wind than larger droplets. During their flight, the temperature reduction of the droplets depends on their sizes and the flight time. The freezing model, derived from Horjen (2015) and Lozowski et al. (2000), takes into account intermittent spraying and run-off. The ice accretion rate of the freezing model depends on the spray flux and the droplet temperature of the spray.

The ice accretion rates that result from SHIPICE are comparable with the data obtained from two observed full scale icing events: (1) on the KV Nordkapp (1987) and (2) on the Atlantic
Kingfisher (2006). SHIPICE is initially developed to determine the ice growth and total amount of ice at relatively large areas on a ship. Therefore, minor effects are not taken into account. As a recommendation for further research, the velocity distribution in z-direction should be reviewed, to improve the obtained spray distribution over the deck of the ship.

The further development of SHIPICE allows users to forecast the amount of ice growing on particular areas on the ship, depending on the expected sea states and air temperatures. Additionally, it will provide an improved basis for regulations and guidelines in an Arctic environment.
Preface

This thesis is submitted to the Delft University of Technology (TU Delft) for the fulfilment of the requirements for the master degree.

This master thesis has been performed at the Research and Development (R&D) department of MARIN, Wageningen, and the department of Offshore and Dredging Engineering, TU Delft, with Jeroen Hoving (TU Delft) and Albert Aalbers (MARIN) as main supervisors and with co-supervisors Professor Thijs Vlugt and Gus Cammaert.

This work is part of the SALTO JIP (Safe Arctic Logistics, Transport & Operations), which concerns the development of a scenario simulation tool to help industry to prepare for the Arctic. SALTO JIP is an initiative of MARIN, Canatec, AKAC Inc., DMI and IMARES.
Acknowledgements

During my thesis many people contributed to my work. First of all, I would like to thank my supervisor within MARIN: Albert Aalbers for his assistance during this project. There was always time to discuss the problems I had with him.

I would like to thank my supervisors from Delft University of Technology: Jeroen Hoving, Gus Cammaert, and Thijs Vlugt for the needed help and advising during my thesis. In the beginning of my thesis I had contact with Ivar Horjen, who send me a copy of his Doctor thesis and his latest paper. I want to thank him for sending his report and paper, which helped me a lot during my thesis.

I would like thank my father Peter Hoes and my cousin Serge Rodrigues Monteiro, who reviewed my thesis during the last months of my thesis. Coming up with some good advise during this last phase.

Finally I want to thank all my family and friends for supporting me during this time.

Thank you all!

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List of Abbreviations and Symbols

List of Abreviations

CFD  Computational Fluid Dynamics
ICEMOD  Icing model developed in 1986 by Horjen and Vefsnmo
JIP  Joint Industry Project
MARICE  Icing model developed in 2014 by Kulyakhtin
MARIN  Maritime Research Institute Netherlands
MIMS  Marine Icing Monitoring System
MSL  Mean Sea Level
ODE  Ordinary Differential Equation
RIGICE  Icing model developed in 1987 by Roebber and Mitten
SALTO  Safe Arctic Logistics, Transport & Operations
SHIPICE  Name of the developed icing model
TU Delft  Delft University of Technology

List of Symbols

$\alpha$  Albedo of ice
$\alpha_N$  Flare angle of the bow at station N
$\alpha_{imp}$  Impact angle of the impinging droplet [$^\circ$]
$\alpha_{mc}$  Slenderness ratio of the micro-columns
$\beta$  Recovery factor
$\delta$  Bow shape angle
$\dot{\varepsilon}$  Strain rate per second
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<th>Symbol</th>
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<tr>
<td>$\gamma$</td>
<td>Surface energy of ice [J/m]</td>
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<td>$\mu$</td>
<td>Wind and wave heading angle [deg]</td>
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<td>$\mu_b$</td>
<td>Dynamic viscosity of the water film [kg/ms]</td>
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<td>$\mu_i$</td>
<td>Friction coefficient of the ice</td>
</tr>
<tr>
<td>$\nabla_t$</td>
<td>Differential operator in the tangetial direction</td>
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<td>$\nu$</td>
<td>Poisson’s ratio</td>
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<tr>
<td>$\nu_a$</td>
<td>Kinematic viscosity of air</td>
</tr>
<tr>
<td>$\nu_w$</td>
<td>Kinematic viscosity of water [m$^2$/s]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Wave frequency [1/s]</td>
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<tr>
<td>$\omega_e$</td>
<td>Encounter radial frequency [1/s]</td>
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<td>$\phi(t)$</td>
<td>Angle of the roll motion [°]</td>
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<td>$\phi_a$</td>
<td>Maximum amplitude of the roll motion [°]</td>
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<td>$\phi_c$</td>
<td>Angular position from the windward stagnation point [degree]</td>
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<tr>
<td>$\phi_{run}$</td>
<td>Angle of the camber and roll motion of the ship [°]</td>
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<td>$\psi(t)$</td>
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<td>$\rho_b$</td>
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<td>$\rho_i$</td>
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<td>$\sigma$</td>
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<td>$\theta(t)$</td>
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<td>$\varepsilon$</td>
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<td>$d_{gr}$</td>
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Evaporative heat flux for droplet cooling

Young’s modulus of ice [Pa]

Saturation vapour pressure [Pa]

Young’s modulus of freshwater ice [Pa]

Impact frequency [1/s]

Peak impact force of a single droplet [N]

Global (direct and diffuse) solar radiation [W/m²]

Gravitational acceleration

Local convective heat transfer coefficient [W/m²K]

Convective heat transfer coefficient of the droplet

Specific enthalpy of the incoming spray [kJ/kg]

Convective mass transfer coefficient of the droplet [m/s]

Length of the micro-columns

Specific enthalpy of the run-off volume [kJ/kg]

Ice accretion rate [kg/m²s]

Thermal conductivity of the air stream

Thermal conductivity of ice [W/mK]

Fracture toughness

Characteristic length of the component [m]

Latent heat of fusion [kJ/kg]

Specific latent heat of vaporization [kJ/kg]

Length of station 21

Mass of the droplet

Nusselt number

Atmospheric pressure [Pa]

Prandtl number

Sum of all the heat fluxes [W/m²]

Saturation specific humidity at air temperature [g/kg]

Convective heat flux [W/m²]

Heat flux of the impinging spray [W/m²]

Saturation specific humidity at droplet temperature [g/kg]

Evaporative heat flux [W/m²]

Conductive heat flux through the ice layer [W/m²]

Radiative heat flux [W/m²]

Heat flux of the adiabatic compression of air and viscous work in the air boundary layer [W/m²]

Heat flux of the run-off volume [W/m²]

Radiative heat flux for droplet cooling

Mass flux of incoming spray [kg/m²]

Relative humidity

Mass flux of run-off volume [kg/m²]
List of Abbreviations and Symbols

\[ R_{wf} \] Mass flux of the water film \([\text{kg}/\text{m}^2\text{s}]\)
\[ Re \] Reynolds number
\[ S_B \] Salinity of the water film \([\text{ppt}]\)
\[ S_i \] Salinity of the ice layer \([\text{ppt}]\)
\[ S_w \] Salinity of seawater \([\text{ppt}]\)
\[ Sc \] Schmidt number
\[ Sh \] Sherwood number
\[ T \] Wave period \([\text{s}]\)
\[ T_a \] Air temperature
\[ T_B \] Water film temperature \([\text{°C}]\)
\[ T_d \] Droplet temperature
\[ T_f \] Freezing temperature of the water film \([\text{°C}]\)
\[ T_i \] Temperature of the ice layer \([\text{°C}]\)
\[ t_N \] Time of the water jet to reach the deck edge
\[ T_{enc} \] Wave encounter period \([\text{s}]\)
\[ T_{per} \] Spraying period \([\text{s}]\)
\[ T_{spray} \] Spraying duration \([\text{s}]\)
\[ T_t \] Temperature of the structure \([\text{°C}]\)
\[ U \] Absolute wind velocity
\[ v_a \] Air volume fraction
\[ v_b \] Run-off velocity of the water film \([\text{m}/\text{s}]\)
\[ V_d \] Initial droplet velocity
\[ V_t \] Terminal velocity of the droplet
\[ \nu_r \] Total void volume fraction
\[ V_x \] Local initial velocity in x-direction
\[ V_y \] Local initial velocity in y-direction
\[ V_z \] Local initial velocity in z-direction
\[ v_{bi} \] Brine volume fraction of saline ice
\[ V_{crit} \] Critical velocity \([\text{m}/\text{s}]\)
\[ V_{dr,T} \] Total relative initial droplet velocity
\[ V_{dr} \] Local initial droplet velocity on the ship
\[ V_{x,jet} \] Initial jet velocity in x-direction
\[ V_{y,jet} \] Initial jet velocity in y-direction
\[ V_{z,jet} \] Initial jet velocity in z-direction
\[ X \] Local water amount per unit area \([\text{kg}/\text{m}^2]\)
\[ x \] Starting x-location
\[ y \] Starting y-location
Chapter 1

Introduction

1-1 Introduction

Due to the declining ice coverage of the Arctic sea (Figure 1-1) in the last years, especially during the summer period, there is more open water in these areas. Now that these areas have no ice any more, there will be more transportation but also more and more marine icing events. The operations of ships in Arctic conditions are delayed and endangered by icing. The economic consequence of ships that cannot fulfil their operation is large, and the cost of de-icing equipment is also quite significant (and power consuming). The risks of marine icing are mainly: blocking of operational equipment, slippery deck, ladders and rails, blocking evacuation and fire fighting equipment, and influence on the stability of the ship, which may lead to capsizing.

The SALTO JIP (Safe Arctic Logistics, Transport & Operations) concerns the development of an approach for safe transport in the Arctic region: a scenario simulation tool to help industry to prepare for the Arctic. In 2013 a pre-study within MARIN started to develop a probabilistic model for icing due to spray water over the bow of a ship. The investigation has two stages: 1. a probabilistic model for volumes of spray water (and the break-up in droplets) rising above the free-board and, 2. a model for the ballistic and thermodynamic process of these droplets when falling and freezing to the ship. In the beginning of 2015 the first stage was finished, the input values of this first stage where used in this report, which concerns the second stage. The development of a marine icing model will allow us to dimension pre-cautions to the area and time of operation, in a probabilistic risk based approach.

1-2 Previous icing models

In previous decades icing models have been developed, but due to the many physical processes involved in icing, many of these processes have not been described in the models. The four
best known icing models are ICEMOD (Horjen, 1990; Horjen and Vefsmo, 1986), RIGICE (Roebber and Mitten, 1987), USCGC Midgett model (Zakrzewski et al., 1988) and MARICE (Kulyakhtin, 2014). Below these four models will be discussed further. All these models are not completely been verified by field measurements, so they can be used as a rough estimation only. The lack of field measurements is still one of the major problems of icing models.

1-2-1 ICEMOD

ICEMOD is a Norwegian model developed in 1986 and later modified in 1988 at the Norwegian Hydrotechnical Laboratory in Trondheim by Horjen and Vefsmo (1986). This model is fully time-dependent. In 2013 the one-dimensional ICEMOD model is improved to a two-dimensional ICEMOD2 model (Horjen, 2013) and currently this model is improved again into ICEMOD2.1 (Horjen, 2015). This model applies a used defined median droplet diameter between 1.8 and 3.8 mm.

1-2-2 RIGICE

In 1987 RIGICE was developed to determine icing norms and extremes for offshore structures located in Canadian waters. It was intended to be a model that runs quickly (still between 10 and 30 minutes). That is why it contains several simplifications to existing models, like ICEMOD. In 2005 the model was upgraded to RIGICE04 (Forest et al., 2005), this model had a number of improvements. The spraying data for this model was obtained from data of the Tarsiut Island (Forest et al., 2005). From this data they made a new liquid water content equation, which produces a more realistic spray flux. They used a median droplet diameter of 1.75 mm.

Figure 1-1: The ice coverage of the Arctic in 2010, showing that during the summer months (September) the transportation routes through the Arctic are open.
The ICEMOD and RIGICE models were developed to determine the icing on offshore rigs instead of ships, although later on in the process ICEMOD also include icing predictions for ships. Note that offshore rigs have no forward speed.

1-2-3 USCGC Midgett model

The USCGC Midgett model is specifically developed for ships, based on the USCGC Midgett full scale test campaign, in cooperation with the University of Alberta. This model is time-dependent with a quasi-deterministic character. Mostly the mass flux will be the limiting factor of the ice growth, but during heavy spraying events and/or warmer conditions, thermal fluxes rather than mass fluxes will be the limiting factor. In this model the trajectory of the droplets is determined with a droplet diameter of 1.75 mm.

1-2-4 MARICE

MARICE is a CFD model developed by Kulyakhtin (2014). It includes the turbulent air flow of an air stream around a ship. Due to the modelling in CFD the model can predict the spray flow and heat transfer around a structure with any shape. This model mainly focuses on the turbulent water droplet flow around the structure. Kulyakhtin uses droplet diameters smaller than 2 mm, the diameters of 1-2 mm are assumed large droplets.

What all these models have in common is that they not include a proper model of the sea spray generation, meaning that they will not use different droplet sizes and velocities. Also the quantities of spray generated are based on quite simple empirical assumptions.

1-3 Scope and Objectives

This master thesis study focuses on the development of an new marine icing model: SHIPICE, that applies the probabilistic sea spray generation model of Aalbers and Poen (2015) as an input. Due to the fact that the input data is probabilistic the whole model will be a probabilistic sea spray icing model. The model considers the droplets separately, with stochastically distributed droplet diameters and initial velocities. In all the previously mentioned models (Section 1-2) the spray generation process is included very simplified and is assumed that the droplet diameters and initial velocities are all the same.

The SHIPICE model can be divided in two parts (Figure 1-4):

1. The droplet trajectory, including the movement of the droplet and the cooling of the droplet during the trajectory time;
2. The droplet freezing on the ship, including droplet freezing, run-off and periodic icing.

From part 1 a hit area intensity distribution will be determined, which will look at the location where the spray hits the ship. In part 2 the amount of ice accretion per hour will be determined. This will be the main part of the research.
To include a research item in the icing models, there will be looked at the impact of the incoming spray on the already accreted ice on the ship. Will this spray impact break off or deform the accreted ice or has this no influence on the ice accretion rate? Due to the time limit of the project there was only a literature study done on this aspect.

1-4 Thesis structure

The theory of marine icing and spray impact will be described in Chapter 2 and Chapter 3. The used methods during the programming stage in Matlab will be described in Chapter 4. The verification of the SHIPICE model is described in Chapter 5. The results of the model and the validation with icing data and other models will be done in Chapter 6. In this Chapter also the found results will be analysed and discussed. The final conclusions of the thesis can be found in Chapter 7 and in Chapter 8 the recommendations for further work on the SHIPICE model are found.
2-1 Icing

Icing can be caused by atmospheric and marine conditions (spraying of seawater), when the air temperature is below the freezing temperature of the water and the spray is above the edge of the ship. Other parameters that influence the marine icing are strong wind and low sea temperatures. In Table 2-1 can be seen that the influence of sea spray is the major reason of marine icing. The low value in the Arctic region is caused because most of the Arctic sea is covered with ice, causing less sea spray icing.

2-1-1 Atmospheric icing

Atmospheric icing is caused by fog, snow, moisture and freezing rain. This type of icing can also occur onshore on electric power cables or wind turbines for example. The atmospheric icing conditions tend to be less frequent and result in smaller icing accretion than sea spray. In the rest of this thesis there will not be looked at atmospheric icing.

Table 2-1: Causes of icing on ships

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of Observations</th>
<th>Sea Spray</th>
<th>Spray, Fog, Rain, Snow</th>
<th>Other Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Seas</td>
<td>400</td>
<td>89</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>North Pacific, North Atlantic</td>
<td>3000</td>
<td>89.8</td>
<td>7.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Arctic</td>
<td>Unknown</td>
<td>50</td>
<td>41</td>
<td>9</td>
</tr>
<tr>
<td>Gulf of St. Lawrence</td>
<td>100</td>
<td>81</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Scotian Shelf</td>
<td>536</td>
<td>94.2</td>
<td>3</td>
<td>2.8</td>
</tr>
<tr>
<td>Grand Banks</td>
<td>100</td>
<td>97</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>NE Newfoundland Shelf</td>
<td>233</td>
<td>95.9</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Labrador Sea and Davis Strait</td>
<td>72</td>
<td>86.9</td>
<td>11.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>
2-1-2 Marine icing

Marine icing exist out of two parts: the impact- and the wind-generated part. Impact-generated sea spray is created by the wave interaction with the structure wall or ship. Wind-generated sea spray are the droplets that are blown off the wave crests, it is generally related to ‘white capping’ which only occurs for wind speeds higher than 9 m/s. During this thesis there will only be looked at impact-generated sea spray, because this is the main part of the marine icing. According to Kulyakhtin (2014) the wind-generated sea spray is unlikely to create a significant contribution to icing. In the paper from Aalbers and Poen (2015) the equations used for the wave-ship generated sea spray can be found, which are used in the rest of this thesis.

2-2 Thermodynamics of the spray droplets

2-2-1 Spray flow

The spray flow of the droplets is based on the calculated sea spray generation of Aalbers and Poen (2015). This will divide the spray in a droplet size distribution. They considered two mechanisms for spray: 1, slamming events, which is an almost explosive spray cloud going up directly after impact of the wave against the bow of the ship and 2, rapid immersion events, the secondary jet that follows from the relative motion of the wave against the ship. The rapid immersion events have a droplet diameter depending on the jet conditions, characteristic values are between 1 and 280 mm. The slamming events create smaller droplets with typical diameter between 1 and 50 mm. In the stochastic approach, each droplet-class has its own mean droplet diameter and initial droplet velocity in x-, y- and z- direction, starting at the edge of the ship where the wave spray is separated from the ship. In Figure 2-1 the conventional coordinate system of a ship is shown. Where the z-axis is positive pointing upward, the x-axis is positive toward the front of the ship and the y-axis is positive directed to the port side of the ship. The z-axis has its origin at the keel K, the x-axis at the aft and the y-axis in the centre-line of the ship. For the ballistic trajectory the z-axis will have its origin at the deck of the ship.

The droplets are assumed to be spherical, and coalescence is ignored because turbulence is not taken into account in this project. Also the effect of evaporation along the trajectory on the droplet mass can be neglected for droplets with diameters larger than 200 µm, although the evaporative heat flux will be taken into account during droplet cooling. The droplet motion equation is controlled by air drag and gravity and half the area of a sphere, not the area of a circle (Hansen, 2012; Kulyakhtin, 2014; Lozowski et al., 2000):

\[
\frac{dV_d}{dt} = -\frac{1}{2}C_d\pi \frac{d^2}{4} \rho_a |V_d - U| (V_d - U) - g m_d
\]

where \(m_d\) is the droplet mass, \(V_d\) the initial droplet velocity \(d\) the droplet diameter, \(\rho_a\) the air density, \(U\) the absolute wind velocity at 10 m height above Mean Sea Level (MSL), \(g\) the gravitational acceleration and \(C_d\) the air drag coefficient. In the article of Lozowski et al. (2000) the \(C_d\) is given by the formula according to Langmuir et al. (1946). They used only one
droplet diameter (1.75 mm). In this project two different equations are used to calculate the droplet drag coefficient depending on their Reynolds numbers, Re (Hoerner, 1965; Morrison, 2010), because there is a large range of different droplet diameters, for the largest droplets the Reynolds number can become larger than $10^6$.

$$C_d = \begin{cases} 
\frac{24}{Re} + \frac{2.6 \frac{Re}{5.0}}{1 + \left(\frac{Re}{570}\right)^{1.52}} + \frac{0.411}{1 + \left(\frac{Re}{263,000}\right)^{8.0}} + \frac{Re^{0.8}}{461,000} & \text{if } 2 < Re \leq 10^6 \\
0.19 - \frac{8 \times 10^4}{Re} & \text{if } Re > 10^6 
\end{cases}$$

(2-2)

where $Re$ is the dimensionless droplet Reynolds number, which can be calculated with:

$$Re = \frac{d|V_{dr} - U|}{\nu_a}$$

(2-3)

where $\nu_a$ is the kinematic viscosity of air, $V_{dr}$ the local initial droplet velocity on the ship, meaning that $Re$ will only be calculated for the initial conditions. In Figure 2-2 the experimental data of Morrison (2010) are shown. Where for the local initial $x$, $y$ and $z$ velocities with respect to the moving ship the following formulas are used Figure 2-3(a):

$$V_x = V_{x,\text{jet}} + U \cos(\mu)$$

(2-4)

$$V_y = V_{y,\text{jet}} + U \cos(\mu)$$

(2-5)

$$V_z = V_{z,\text{jet}}$$

(2-6)

$$V_{dr,T} = \sqrt{V_x^2 + V_y^2 + V_z^2}$$

(2-7)
8 Marine Icing Theory

Figure 2-2: Data of the experiment executed by Morrison (2010) according to Eq. (2-2), the drag coefficient according to the entire Reynolds number range.

Where \( V_x, V_y \) and \( V_z \) are the local initial velocities in x, y and z-direction on the ship, respectively, \( V_{x,\text{jet}}, V_{y,\text{jet}} \) and \( V_{z,\text{jet}} \) the initial jet velocities where the ships speed is already included in the spray generation equations (Aalbers and Poen, 2015), \( \mu \) the wind heading angle and \( V_{d_r,T} \) the total relative initial velocity of the droplet. The ships velocity is not included in these equations, because this velocity is already included in \( V_{i,\text{jet}} \), with i the x, y or z-direction, see Eq. (2-8) and Eq. (2-9) for station 21:

\[
V_{i,\text{jet}} = \begin{cases} 
-V_s 
& \text{for } x\text{-direction} \\
V_{i,\text{jet},N} \sin(\alpha_N) - V_z \tan(\varepsilon_N) 
& \text{for } y\text{-direction} \\
V_{i,\text{jet},N} \cos(\alpha_N) - g t_N 
& \text{for } z\text{-direction}
\end{cases}
\]  

\[
V_{i,\text{jet},21} = \begin{cases} 
-V_s + V_{i,\text{jet},21} \sin(\alpha_{21}) \sin(\varepsilon_{21}) 
& \text{for } x\text{-direction} \\
V_{i,\text{jet},21} \sin(\alpha_{21}) \cos(\varepsilon_{21}) - V_z \sin(\alpha_{21}) \sin(\varepsilon_{21}) 
& \text{for } y\text{-direction} \\
V_{i,\text{jet},21} \cos(\alpha_{21}) - g t_{21} 
& \text{for } z\text{-direction}
\end{cases}
\]

where \( \alpha_N \) is the flare angle of the bow, \( t_N \) the time needed for the water jet to go from the waterline to the deck edge and \( \varepsilon_N \) the buttock angle (angle of the waterline).

**Droplet break-up**

Droplet break-up is the process of a droplet breaking up in smaller droplets due to air shear stresses, depending on droplet size and velocity. In most of the previous models, droplets with a diameter smaller than 5 mm are used (Horjen and Vefsnmo, 1986; Kulyakhtin, 2014; Lozowski and Zakrzewski, 1992; Lozowski et al., 2000). The droplet diameter size from the model of Aalbers and Poen (2015) varies typically between 1 and 280 mm. Although these droplets are generally larger than 5 mm, a secondary break-up will not be included, because the break-up time is almost always larger than the trajectory time.
2-2 Thermodynamics of the spray droplets

Figure 2-3: (a) Velocities converted to the local coordinate system of the ship in the x- and y-direction. (b) Heading of the wind and waves.

Figure 2-4: Droplet diameter against the relative velocity of the droplet (Faeth et al., 1995).

2-2-2 Droplet cooling

During the droplet trajectory the droplet will be cooled due to a temperature difference between the droplet and the air. The initial droplet temperature is taken to be the same as the sea water temperature. Inside of the droplet the temperature gradient will be ignored, assuming a thermally homogeneous droplet. There can also be assumed that the droplets during the trajectory will not freeze, if they will come beneath the freezing temperature they become supercooled. The droplet cooling equation is controlled by the convective, $C$, evaporative, $E$, and long-wave radiant, $R$, heat fluxes (Lozowski et al., 2000; Zarling, 1980). The process may described in a differential equation:

$$m_d c_w \frac{dT_d}{dt} = \pi d^2 (C + E + R) \quad (2-10)$$
where $c_w$ is the specific heat capacity of water and $T_d$ is the droplet temperature. The heat fluxes have been defined following Lozowski et al. (2000).

$$C + E + R,$$

$T_d$

**Figure 2-5:** Droplet with his boundary system and the heatfluxes acting on the droplet.

Convective heat flux:

$$C = h_c(T_d - T_a) \quad (2-11)$$

$$h_c = \frac{Nu k_a}{d} \quad (2-12)$$

$$Nu = 2 + 0.6Pr^{0.33}Re^{0.5} \quad (2-13)$$

where $h_c$ is the convective heat transfer coefficient of the droplet, $T_a$ the air temperature, $Nu$ the droplet Nusselt number, the ratio of convective and conductive heat transfer normal to the water-air boundary layer, $k_a$ the thermal conductivity of the air stream, and $Pr$ the Prandtl number of the air stream, the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity.

Evaporative heat flux:

$$E = h_v \rho v l_v(q_d - q_a) \quad (2-14)$$

$$h_v = \frac{Sh D_w}{d} \quad (2-15)$$

$$Sh = 2 + 0.6Sc^{0.33}Re^{0.5} \quad (2-16)$$

where $h_v$ is the convective mass transfer coefficient of the droplet, $l_v$ the specific latent heat of vaporization at the droplet temperature, $q_d$ the saturation specific humidity at the droplet temperature, $q_a$ the saturation specific humidity at the air temperature, $Sh$ the droplet Sherwood number, also called the mass transfer Nusselt number, $D_w$ the mass diffusivity of water vapour in air, and $Sc$ the Schmidt number of the air stream, the ratio of momentum diffusivity (kinematic viscosity) to mass diffusivity.

Long-wave radiative heat flux:

$$R = \varepsilon \sigma (T^4_d - T^4_a) = 4.48(T_d - T_a) \quad (2-17)$$

where $\varepsilon$ is the droplet emissivity, the effectiveness in emitting energy as thermal radiation, and $\sigma$ the Stefan-Boltzmann constant. The cooled droplet temperature will be one of the inputs for the icing equations.
2-3 Icing

The ice growth process of every icing model starts with a liquid water film on the structure or already accreted ice layer. Due to the salinity of sea water there will be mostly wet icing on the ship. In seldom cases, if the spray flux is sufficiently low and the air temperature sufficiently cold, it is possible to have dry icing, meaning that all the ice will freeze immediately without a water film layer.

2-3-1 Wet icing

For the determination of the icing rate, any temperature difference in the water layer is ignored because this layer is so thin that the variations in temperature are nihil. In Figure 2-6 the used heat, mass and salt balances of the water film layer are shown schematically. The red dotted line around the water film is the control volume boundary in which the heat balance is applied. In these three figures there will be assumed ice accretion on a vertical wall, but the same balances can be used for ice accretion on horizontal or inclined surfaces.

Figure 2-6: Conservation of heat(a), mass(b) and salt(c).

Below is the heat, mass, and salt balance of this water layer, see Figure 2-6 (Hansen, 2012; Horjen, 1990). Further explanation about these balances can be found in Appendix A.

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Marine icing
\begin{align*}
    c_b X \frac{\partial T_b}{\partial t} &= I (1 - \sigma_M) l_f - Q_c - Q_e - Q_r + Q_d - Q_{\text{run}} + Q_v - Q_i \tag{2-18} \\
    \frac{\partial X}{\partial t} + \nabla_t (v_b X) &= R_d - I \tag{2-19} \\
    \frac{\partial X S_b}{\partial t} + \nabla_t (v_b X S_b) &= R_d S_w - I S_b \sigma_M \tag{2-20}
\end{align*}

In which $T_b$ is the temperature of the water film, assumed to be the same as the freezing temperature, $T_f$ the equilibrium freezing temperature of the water depending on the salinity, $S_b$ the salinity of the water film, $c_b$ the specific heat of the water, $X$ the local water amount per unit area [kg/m$^2$], $I$ the ice accretion rate ($I = \rho_i \frac{db}{dt}$, with $\rho_i$ the density of ice), $b$ the ice thickness, $\sigma_M$ the mass ratio of entrapped liquid water in the ice accretion layer close to the ice/water film interface. According to several wind tunnel experiments of Makkonen: $\sigma_M = 0.34$ (Horjen, 1990; Makkonen, 2010). $R_d$ is the mass flux of the incoming spray, $h_d$ the specific enthalpy of the incoming spray, $R_{\text{run}}$ the mass flux of the run-off volume, $h_{\text{run}}$ the specific enthalpy of the run-off volume, $v_b$ the run-off velocity of the water film, $\nabla_t$ the differential operator in the tangential direction (the direction along the water movement), $S_w$ the salinity of the seawater and $Q_c$, $Q_e$, $Q_r$, $Q_d$, $Q_{\text{run}}$, $Q_v$ and $Q_i$ are the convective (or sensible), evaporative (or latent), radiative, heat content of the impinging spray, heat content of the run-off, adiabatic compression of air and viscous work in the air boundary layer and conductive (through the ice layer) heat fluxes, respectively.

Notice that the mass flux due to evaporation will be neglected in these equation, because this amount of mass is negligible compared with the mass flux for run-off and ice accretion. Further explanations of the heat, mass and salt balance can be found in Section 2-3-2.

### 2-3-2 Freezing of the water film

The freezing temperature of the water film layer, $T_f$, depends on the salinity of the water film, $S_b$ (Hansen, 2012):

\[
    T_f = \begin{cases} 
    5.4113 \times 10^{-2} S_b & \text{if } S_b < 125 \\
    9.7007 \times 10^{-2} S_b \frac{1 - 10^{-3} S_b}{1 - 10^{-4} S_b} + 6.0533 & \text{if } 125 \leq S_b < 230 
    \end{cases} \tag{2-21}
\]

The ice growth from the spray generation depends on the environmental aspects (long term) and the spraying event (short term) influence. When the spray reaches the cold surface structure the ice growth rate is generated by seven heat fluxes, based on the heat balance, Eq. (2-18). The left-hand side of Eq. (2-18) is the change in internal energy within the water layer. Note that the temperature of the water film is assumed homogeneous, so that through the water layer the temperature difference is zero. For a continuous icing process there will be no difference in the water film temperature over time. Meaning that all incoming heat fluxes will only have influence on the ice growth. Giving the following equation for the conservation of heat (Horjen, 1990; Kulyakhtin, 2014; Lozowski et al., 2000):
\[ l_f (1 - \sigma_M) \rho_i \frac{db}{dt} = Q_c + Q_e + Q_r - Q_d + Q_{run} - Q_v + Q_i \]  
(2-22)

where \( l_f \) is the latent heat of fusion (333.4 kJ/kg). Because the thickness of the water film is quite small, smaller than 1 mm, the water layer can be assumed isothermal. Meaning that the temperature of the water is assumed the same as the freezing temperature of ice. Below the formulas for the different heat fluxes are determined.

\[ Q_c = h(T_f(S_b) - T_a) \]  
(2-23)

where \( h \) is the local convective heat transfer coefficient, which depends on the Nusselt number, \( Nu \):

\[ h = \frac{Nu k_a}{L} \]  
(2-24)

where \( L \) is the characteristic length of the component and the Nusselt number is different for planar and cylindrical components (Horjen, 2015; Kulyakhtin, 2014):

\[ Nu_{pl} = 0.036 Pr^{0.33} Re^{0.8} \]  
(2-25)

\[ Nu_{cyl} = \begin{cases} 
(-1.82 \cdot 10^{-8} \phi_c^3 + 9.18 \cdot 10^{-7} \phi_c^2 + 1.49 \cdot 10^{-4} \phi_c + 8.39 \cdot 10^{-3}) Re^{0.86} & \phi_c < 130^\circ \\
(-5.85 \cdot 10^{-8} \phi_c^3 + 2.74 \cdot 10^{-5} \phi_c^2 - 4.18 \cdot 10^{-3} \phi_c + 0.212) Re^{0.86} & \phi_c \geq 130^\circ 
\end{cases} \]  
(2-26)

The Reynolds number, \( Re \), is here defined using the relative wind speed and the characteristic length of the component (diameter of the cylinder or maximum length dimension of the planar component). On a cylindrical shape \( \phi_c \) is the angular position from the windward stagnation point in degrees. In this report there will only be looked at planar components.

\[ Q_e = \frac{\varepsilon_{mw} l_v}{P_a c_a 0.9} h(e_s(T_f(S_b)) - r_H e_s(T_a)) \]  
(2-27)

where \( \varepsilon_{mw} \) is the ratio of the molecular weight of water vapour and dry air, \( l_v \) the specific latent heat of vaporization at the water film temperature, \( P_a \) the atmospheric pressure, \( r_H \) is the relative humidity of the air. \( e_s(T) \) is the temperature dependent saturation vapour pressure, which is calculated with the Bolton formula for fresh water, neglecting the effect of salinity (Lozowski et al., 2000):

\[ e_s(T) = 611.2 \exp \left( \frac{17.67 T}{T + 243.5} \right) \]  
(2-28)

The radiative heat flux exist of two terms, namely the long wave radiation, which is emitted by the ice surface, and the short wave radiation, emitted by sun light. (Gauthier et al., 2013; Lozowski et al., 2000):

\[ Q_r = G(1 - \alpha) + 4.48(T_f(S_b) - T_a) \]  
(2-29)

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where $G$ is the global (direct and diffuse) solar radiation, $\alpha$ the albedo of ice, for newly formed sea ice $\alpha=0.3$. Because most of the icing events happen during the autumn and winter season with little light and after stormy conditions, the effect of the sun is usually neglected for icing formation\(^1\), thus the first part of the radiation heat flux can be neglected:

$$Q_r = 4.48(T_f(S_b) - T_a) \quad (2-30)$$

The heat content of the impinging spray is:

$$Q_d = R_d c_w (T_f(S_b) - T_d) \quad (2-31)$$

where $T_d$ is the mean end temperature of the incoming spray droplets, see Eq. (2-10). Depending on the incoming mean droplet temperature this heat flux has a positive or negative influence on the total icing rate, if the droplet temperature is higher than the freezing temperature it has a negative influence otherwise it is positive. The heat content of the run-off water is given by:

$$Q_{run} = R_{run} h_{run} = R_{run} c_w (T_f(S_b) - T_{wf}) \quad (2-32)$$

where $h_{run}$ is the specific enthalpy of the water film and $T_{wf}$ is the averaged water film temperature, averaged of droplet temperature and water film temperature. The heat flux from work done in the air above the water film, due to friction and adiabatic compression is according to Horjen (1990) approximated by:

$$Q_v = h \beta U_w^2 \rho_c a \quad (2-33)$$

where $\beta$ is the recovery factor. A description and discussion of this contribution can be found in Horjen (1990). This heat flux is constant through the icing process, not depending on the freezing temperature of the water film. The effect of this heat flux is not large compared with the convective, evaporative and radiative heat fluxes. Finally there is the conductive heat flux through the ice layer towards the structure.

$$Q_i = -k_{ice} \frac{T_{st} - T_f(S_b)}{b} \quad (2-34)$$

where $k_{ice}$ is the thermal conductivity of ice, $T_{st}$ the temperature of the structure and $b$ the thickness of the accreted ice layer. The equation assumes a linear temperature gradient through the ice. In the model it is assumed that the structure is insulated and does not have heating. So the temperature of the structure approaches the temperature of the ice, and therefore this heat flux will be neglected. This will give a final equation for the conservation of heat:

$$l_f(1 - \sigma_M) \rho_i \frac{dh}{dt} = Q_c + Q_e + Q_r - Q_d + Q_{run} - Q_v \quad (2-35)$$

\(^1\)For the melting of ice the effect need to be included.
2-3-3 Dry icing

As mentioned in Section 2-3 dry icing can occur when the spray flux of the impinging spray and the air temperature are sufficiently low. All the incoming spray will than freeze during the impact, giving \( I = R_d \). The dry icing event will occur if (Hansen, 2012; Horjen, 1990):

\[
\rho_i \frac{db}{dt} = I = R_d < -\frac{Q_c + Q_e + Q_r}{\frac{Q_d}{R_d} + l_f(1 - \sigma_M)}
\]  

(2-36)

2-3-4 Run-off

When the spray arrives at the deck not all the water will freeze, but a part of it will run off the ship, for which Eq. (2-19) and Eq. (2-20) are proposed to model this effect:

\[
\frac{\partial X}{\partial t} + \nabla (v_b X) = R_d - I \\
\frac{\partial XS_b}{\partial t} + \nabla (v_b XS_b) = R_d S_w - IS_b \sigma_M
\]

On the vertical parts of the deck structures a large part will run-off and on the deck there will be a small run-off part due to the camber of the ship and the ship motion of the ship. The average run-off velocity of the water film is based on the dynamic shear viscosity, \( \tau = \mu du/dy \). In order to simplify the equation there will be assumed a linear flow distribution (Hansen, 2012; Horjen, 1990, 2013; Kulyakhtin, 2014):

\[
v_b = -\frac{\rho_b \eta^2 g}{3 \mu_b} |\sin(\phi_{run})|
\]

(2-37)

where \( \rho_b \) is the water film density, \( \mu_b \) the dynamic viscosity of the water film and \( \phi_{run} \) the angle of the camber and ship motions or vertical plane (\( \phi_{run} = 90 \) if plane is totally vertical). The shear stress, \( \tau \), is based on the gravitational force and the density and thickness of the water film.

The camber angle is approximately 2°. The camber can be seen as a constant angle and the ship motions as a dynamically changing sinusoidal angle, depending on the sea state.

In this research only the roll motion, \( \phi(t) \), of the ship is considered and not the pitch, \( \theta(t) \), and yaw, \( \psi(t) \) motions, see Figure 2-1 for the direction of these rotational motions. So there will be no run-off in the x-direction (from one section to another) but only in the y-direction.

\[
\ddot{\phi} = \text{camber} + \phi(t) = \text{camber} + \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} \phi_a |\sin\left(\frac{2\pi}{T}t\right)| \, dt
\]

(2-38)

where \( \phi(t) \) is the roll motion of the ship, \( T \) is the wave period, and \( \phi_a \) is the maximum amplitude of the roll motion. In this report there will be assumed that \( \phi_a = 4 \) degree, which is according to ship experience a realistic value for wave conditions from head seas, as are relevant for spraying.
The actual water film flux of the run-off is based on the run-off velocity, from Eq. (2-19). The run-off water film mass flux can be determined (Hansen, 2012; Kulyakhtin, 2014), Eq. (2-37):

$$R_{\text{run}} = -\frac{\rho_b \eta^2 g}{3 \mu_b} \sin(\phi_{\text{run}}) |X|$$  \hspace{1cm} (2-39)

### Salinity of the water film

For the determination of the ice accretion rate, the salinity of the water film is considered (Horjen, 1990):

$$S_b = \frac{R_{wf} S_b + R_d S_w}{R_{wf} + R_d - \frac{Q}{L_f}}$$  \hspace{1cm} (2-40)

where $S_b$ is the salinity of the water film, $R_{wf}$ the mass flux of the water film, $S_w$ the salinity of the seawater, and $Q$ the sum of all the heat fluxes mentioned in Section 2-3.

### 2-4 Periodic icing

As mentioned above the effect of $Q_d$ is influenced by the spray flux and spray temperature. During the spray events this heat flux $Q_d$ has influence on the freezing rate and in between the spray events this heat flux will be zero. During the icing process the salinity of the water-film increases in between spray events and decreases when a new spray arrives. The salinity of the water film influences the freezing temperature of the water film, which is quantified in Eq. (2-21). The salinity of the water film is limited by the air temperature, because that is the minimum freezing temperature of the water film. The thickness of the water film will decrease in between spray events, due to ice growth and run-off, and the water film increases when a new spray arrives. Now the change of the internal energy will not be zero and Eq. (2-35) will be:

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\[ l_f (1 - \sigma_M) \rho_l \frac{db}{dt} = Q_v + Q_e + Q_r - Q_d + Q_{run} - Q_v - c_b X \frac{dT_b}{dt} \]  \hspace{1cm} (2-41)

### 2-4-1 Spray and period time

To include the influence of periodic icing, the spray events can be programmed as a unit step response. Where the step response has a value of 1 during the spraying event and 0 in between the events, see Figure 2-8.

The duration of one spraying event, \( T_{spray} \), is calculated with the assumption that a single spray is generated along a distance equal to a quarter of the significant wave length, the upper half of the upward wave motion:

\[ T_{spray} = \frac{T_{enc}}{4} \]  \hspace{1cm} (2-42)

\[ T_{enc} = \frac{2\pi}{\omega_e} \]  \hspace{1cm} (2-43)

\[ \omega_e = \omega - \omega^2 \frac{V_s}{g} \cos(\mu) \]  \hspace{1cm} (2-44)

where \( T_{enc} \) is the wave encounter period, \( \omega_e \) the encounter radial frequency, \( \omega \) the wave frequency, and \( \mu \) the wave direction (180 degree for head seas).

For ship icing, on a fishing trawler, it has been estimated that every second significant wave produces spray (Zakrzewski, 1987). The model of Aalbers and Poen (2015) goes much more in detail for ship motions and provides the dependence of spray events to ship speed and wave direction. In this thesis it is assumed that the spray recurrence period, \( T_{per} \), is averaged equal to:

\[ T_{per} = \frac{\text{Duration of simulation}}{\text{Number of events}} \]  \hspace{1cm} (2-45)

**Figure 2-8**: Example of the unit step response, with \( T_{spray} = 3.11 \text{ s} \) and \( T_{per} = 11.37 \text{ s} \).
The incoming spray will hit the accreted ice with a certain impact, based on the incoming velocity and mass of the spray. Due to this impact splashing will occur when the droplet velocity is high enough. Together with the splashing the droplet will have a certain impact force which can cause the break off or declining of the already accreted ice, see Figure 3-1. Both mechanisms are investigated in this Chapter.

**Figure 3-1:** Illustration of the impact of a single droplet on the water film and the underlying ice.

### 3-1 Spreading or splashing

A first principle approach to the effect of impacts of fluid drops on a fluid layer is made. Useful information is found in an experiment of Yarin & Weiss (1995) about the spray impact...
on thin liquid layers. The experiment was done with mono-disperse ethanol drops (d = 70-340 \( \mu m \) and \( V_d \) up to 30 m/s) on a solid wetted flat surface, where the film thickness of the liquid was relatively large compared to the mean surface roughness. There could occur two different characteristic flow patterns on the liquid film, depending on the impact velocity of the droplets. Yarin (2006) defines a critical velocity, \( V_{crit} \), for drop splashing. If \( V_d < V_{crit} \) drop spreading will occur and drop splashing will occur when \( V_d > V_{crit} \). If there will occur splashing, there can be determined how much of the liquid will splash.

\[
V_{crit} = 18 \left( \frac{\sigma_w}{\rho_w} \right)^{1/4} \nu_{w}^{1/8} f^{3/8}
\]

where \( \sigma_w \) is the surface tension of the water, \( \nu_w \) the kinematic viscosity of water and \( f \) the frequency of the impacts, where \( f \) can be defined by \( f = V_d/d \) for single droplet impacts. To determine if there will occur splashing during icing events, the critical velocity is calculated for different droplet sizes and velocities, see Table 3-1.

Table 3-1: Calculated critical velocity for different droplet sizes and velocities.

<table>
<thead>
<tr>
<th>D [m]</th>
<th>( V_{crit}(V_d = 5) )</th>
<th>( V_{crit}(V_d = 10) )</th>
<th>( V_{crit}(V_d = 15) )</th>
<th>( V_{crit}(V_d = 25) )</th>
<th>( V_{crit}(V_d = 35) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>7.8</td>
<td>10.12</td>
<td>11.78</td>
<td>14.26</td>
<td>16.18</td>
</tr>
<tr>
<td>0.006</td>
<td>3.98</td>
<td>5.17</td>
<td>6.02</td>
<td>7.29</td>
<td>8.27</td>
</tr>
<tr>
<td>0.011</td>
<td>3.17</td>
<td>4.12</td>
<td>4.79</td>
<td>5.8</td>
<td>6.58</td>
</tr>
<tr>
<td>0.016</td>
<td>2.76</td>
<td>3.58</td>
<td>4.16</td>
<td>5.04</td>
<td>5.72</td>
</tr>
<tr>
<td>0.021</td>
<td>2.49</td>
<td>3.23</td>
<td>3.76</td>
<td>4.55</td>
<td>5.17</td>
</tr>
<tr>
<td>0.026</td>
<td>2.3</td>
<td>2.98</td>
<td>3.47</td>
<td>4.2</td>
<td>4.77</td>
</tr>
<tr>
<td>0.031</td>
<td>2.15</td>
<td>2.79</td>
<td>3.25</td>
<td>3.94</td>
<td>4.46</td>
</tr>
</tbody>
</table>

Table 3-1 shows that there only exist spreading for the droplet size of 1 mm, with a droplet velocity smaller than 10 m/s. Causing almost no spreading in the model. Because the experiment of Yarin & Weiss was done for droplet sizes between 70 and 340 \( \mu m \), it is not sure how well this equation is performing for these large droplets in the SHIPICE model. To have a better understanding about the splashing of these larger droplets, experiments should done. In the SHIPICE model the splashing is not included due to the large uncertainty about the equation for these larger droplets. For the horizontal parts on the ship this is not really a big influence, however for the vertical parts the splashing could have some influence on the icing rate.

### 3.2 Break-off of the ice layer

To get insight in what would be the break-off due to the impact force, the first step was to look at erosion of metal plates due to the impact of incoming droplets. However the theory of erosion was mostly based on very high impact velocities and erosion of metal plates which is very different from low impact velocities on ice plates. Because this gave no further insight, the study looked at the formation of ice creams, and their material properties (Seppings, 2006). Also the material properties of sea ice were considered (ISO19906).

Depending on the failure strength of the newly accreted ice and the impact forces, the spray impact can break off the newly formed ice. A few assumptions were made: (1) Only the ice
layer that was formed in the previous spray period can break-off due to the incoming spray, (2) there can only be break-off on the vertical planes on the ship, because on the horizontal planes the broken ice pieces can not flow anywhere, so will freeze back on again.

To determine the peak impact force of a single droplet, $F_p$, the following equation is used (Li et al., 2014):

$$F_p = 8.32 \times 10^{-4} V_d^{1.86} d^{2.02}$$  \hspace{1cm} (3-2)

This equation is based on an experiment of low-speed water droplets colliding on a light aluminium plate, where the impact forces were measured. To measure these forces they used a highly sensitive piezoelectric force transducer. This experiment was done with droplet diameters between 2.28 and 3.1 mm and impact velocities between 1.4 and 3.13 m/s.

If the impact force of the droplets is determined with Eq. (3-2) the normal and shear stresses due to this force will be calculated, see Figure 3-2:

$$\sigma_p = \frac{F_p \sin(\alpha_{imp})}{A}$$  \hspace{1cm} (3-3)

$$\tau_p = \frac{F_p \cos(\alpha_{imp})}{A}$$  \hspace{1cm} (3-4)

where $\sigma_p$ is the normal stress, $\tau_p$ the shear stress, $\alpha_{imp}$ the angle of the impinging droplet with the ship and $A$ the droplet area.

For break-off to occur the applied stresses should be higher than the compressive and shear strength of the newly formed ice, if $\tau_p > \tau_{critical}$ and $\sigma_p > \sigma_{critical}$.

![Figure 3-2: Illustration of the impact force and the reacting stresses on the ice layer.](image)

Now, the critical shear stress for crack nucleation in ice has been given by Gold (1972) (Xu et al., 2004):

$$\tau_{critical} = \tau_e = \left( \frac{\pi \gamma E_i}{4(1 - \nu^2)d_{gr}} \right)^{1/2}$$  \hspace{1cm} (3-5)

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where $\tau_e$ is the effective shear stress, $\gamma$ the surface energy of ice, $\nu$ the Poisson’s ratio of ice, which is 0.3, $d_{gr}$ the grain diameter, Gold used $d = 3$ mm, and $E_i$ is the Young’s modulus of ice. $E$ of saline ice depends on the total brine volume fraction (ISO19906):

$$E_i = E_{fi}(1 - \sqrt{v_{bi}})^4$$

(3-6)

where $E_{fi}$ is the Young’s modulus of freshwater ice, which has a value in the range of 9 GPa to 10 GPa, and $v_{bi}$ is the brine volume fraction of saline ice. In Section 2-3 the liquid water fraction in the accreted ice layer close to the water/ice film interface is $\sigma_M = 0.34$, this is assumed to be the same as the brine volume fraction, $v_b$, of the ice. For fully developed ice the brine volume fraction of sea ice can be determined by the following equation (ISO19906):

$$v_{bi} = S_i \left( \frac{49.18}{|T_i|} + 0.53 \right)$$

(3-7)

where $S_i$ is the salinity of the ice layer, $S_i = \sigma_M S_b$, and $T_i$ the ice temperature in degree Celsius assuming this will be the same as the freezing temperature of the water film. The brine volume fraction is calculated in ppt, parts per thousand. The salinity of sea ice at -10 degrees Celsius is between 4 and 6 ppt.

For the critical normal compression stress the mechanism of brittle compressive failure was considered. For an ice block with an inclination of the crack of 45 deg, the initiation stress, $\sigma_f$, under normal compressive loading can be determined by (Schulson, 1999):

$$\sigma_{critical} = \sigma_f = \frac{2K_{IC}}{(3\alpha_{mc}h_{mc})^{1/2}(1 - \mu_i)}$$

(3-8)

where $K_{IC}$ is the fracture toughness, $\alpha_{mc}$ the slenderness ratio of the micro-columns, $h_{mc}$ the length of the micro-columns, with $h_{mc} = d_{gr}/2$, and $\mu_i$ the friction coefficient of the ice.

According the ISO19906 regulations the compressive strength of granular sea ice, $\sigma_c$, is determined with the following equation (ISO19906; Timco and Weeks, 2010):

$$\sigma_c = 49\epsilon^{0.22} \left( 1 - \sqrt{\frac{v_T}{0.28}} \right)$$

(3-9)

where $\dot{\epsilon}$ is the strain rate per second and $v_T$ the total void volume fraction ($v_T = v_{bi} + v_a$), where $v_a$ is the air volume fraction in the ice. This equation cannot be used in this thesis, due to fact that $v_{bi} = 0.34$ which is larger than 0.28 giving a negative value for $\sigma_c$.

The influence of the spray impact on the break-off of the accreted ice layer is not been used in the final model, because there are to many uncertainties of the impact of these sprays. Due to the time limits of this MSc. thesis it did not fit in the scope of work.
Chapter 4

Summary of the method

4-1 Introduction

In this chapter the steps during the programming will be discussed. The SHIPICE model will be modelled with the use of Matlab R2015a. In Figure 4-1 the flowchart of SHIPICE is shown, with for every part, the input and output of this part. Eventually all the different parts will give an input for the icing part. The icing part (droplet freezing) will give the final outcome of the model.

![Flowchart of SHIPICE model](image)

Figure 4-1: A flowchart with all the needed steps for this icing model, the input of this model will be the probabilistic sea spray generation model of Aalbers and Poen (2015). The spray impact is also included in this flowchart, but will not be implemented in the icing model.
4-2 Trajectory

The trajectory of the different droplets could be found when putting Eq. (2-1) for the x, y and z direction in the Matlab ODE45 solver, giving a total of 3 different first-order differential equations. The ODE45 within Matlab is based on an explicit Runge-Kutta (4,5) formula. Assuming that the wind velocity will only influence the horizontal direction, the wind effect can be ignored in z-direction. With this solver SHIPICE will find the x, y and z end-location, end-velocity and the trajectory time per droplet-diameter. These end-locations are determined with the 'Event function' within the ODE45 solver.

The drift of the droplets in the wind (carried along with the currents of the wind) can also be ignored, because droplets with a diameter of 200 microns or larger are less influenced by drift factors (Baetens et al., 2009). In this model the droplet diameter size is between 1 and 280 mm. All the droplets will just follow their own trajectory instead of being taken by the wind, influenced a little by the wind and air drag.

Before the trajectory can be calculated there are made a couple of adjustments to the input-file of Aalbers and Poen (2015), for the droplet velocities in x-, y- and z-direction. Also there is looked at the right mesh dependency of the droplets on the edge of the ship.

![Figure 4-2:](image)

**Figure 4-2:** Difference between the droplet distribution on the ship for all the same z-velocities (a) and with a linear z-velocity distribution (b).

4-2-1 Vertical droplet velocity distribution

Based on several slow-motion videos of wave run-up against a structure vertical wall, in a test basin at MARIN, was concluded that drops and blobs in a single spray event do not have everywhere the same velocity. The droplets at the bottom of the spray have a much
lower velocity than the droplets at the top. In Figure 4-2 the difference between the hit area intensity distribution on the deck of a ship can be seen with all the same z-velocities (a) and with a velocity distribution (b). Currently there is not enough known about this process to exactly define the velocity distribution. That is why there was looked at a linear and a Gaussian velocity distribution, see Figure 4-3. The Gaussian velocity distribution is related to the droplet size distribution (Aalbers and Poen, 2015). After comparing the amount of droplets that land on the total area of the ship, for the same meteorological conditions. It is concluded that there is 0.2 litre water per event less for a Gaussian velocity distribution, for the frigate model case with 200 degree wind from the portside bow, given by Sapone (1990). For the amount of droplets on the ship it does not really matter which velocity distribution there is used. Because there is nothing known about the velocity distribution process and it is not a natural stochastic process, the linear and Gaussian velocity distribution will be compared in Section 6-2-1, to determine which velocity distribution should be used in SHIPICE.

**4-2-2 Velocity Station 21**

As can be seen in Figure 4-4 the sides of the ship in station 17 till 21 are simplified as a straight line. For the stations 17 till 20 this seems quite realistic, but for station 21 not. Especially at the front of station 21 you will have a flatter part. To have a more realistic bow for station 21, it can be seen as a parabola. With this adjustment in the shape of the bow, the buttock angle, $\varepsilon_{21}$, and the bow flare angle, $\alpha_{21}$, in Eq. (2-9) will also change. The new buttock angle depends on the location where the droplets start on the bow edge. The sections are divided in multiple start positions, see Section 4-2-3. For every starting position on the bow at station 21 the velocity equation has a different buttock angle:

$$x = -\frac{L_{21}}{(0.5B_{20})^2} y^2 + L_{21}$$  \hspace{1cm} (4-1)

$$\frac{dx}{dy} = -\frac{2L_{21}}{(0.5B_{20})^2} y = \tan\left(\frac{\pi}{2} - \varepsilon_{21}\right)$$  \hspace{1cm} (4-2)
where $L_{21}$ is the length of station 21, $B_{20}$ the width at the boundary of station 20 and 21 and $x$ and $y$ are the starting x and y locations. Eq. (4-1) is the equation for the parabola of the bow and Eq. (4-2) is the equation for the determination of the buttock angle, depending on the derivative of Eq. (4-1). For the determination of the new bow flare angle the following equation is used:

$$
\alpha_{21} = -\tan^{-1}\frac{\sqrt{(x_{\text{start}} - L_{pp})^2 + y_{\text{start}}^2}}{\text{Freeboard}}
$$

(4-3)

Figure 4-4: Simplification of the ship with the different sections, shown only 16 till 21. The dark red part represents a deck structure, which can have different locations on the ship.

4-2-3 Mesh dependency

For a better distribution of the droplets per station, the droplets will have multiple different start positions along the edge of one station. For every station there are looked at 10, 20, or 30 start positions of the droplets.

Figure 4-5: Visualisation of the steps on the bow for station 21, with 10 steps, and the difference between the two starting position cases.
There will not only be looked at the difference in these steps, but also the difference between the starting points of the droplets. For station 21 this is quite relevant, as one case will be with a starting point at the front of the bow and the other with the starting point not exactly at the front (Figure 4-5). Two conditions will be compared for the frigate hull form of Sapone (1990): with wind 200° off the portside bow and with wind from ahead (180°). If the wind is coming from ahead there is also looked at 40, 50, and 60 starting positions.

![Figure 4-6: Intensity distribution of the front off the ship (smooth bow, 200° wind), the two ships above are with a starting point at the front of the bow (a & b) and below with a starting point not exactly at the front of the bow (c & d).](image)

![Table 4-1: Parameters from SHIPICE calculated with the data of Sapone (smooth bow, 200° wind).](table)

<table>
<thead>
<tr>
<th>Starting point</th>
<th>Parameters</th>
<th>10 steps</th>
<th>20 steps</th>
<th>30 steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>Volume on ship ([dm^3/event])</td>
<td>46.2</td>
<td>48.6</td>
<td>51.3</td>
</tr>
<tr>
<td></td>
<td>Percentage difference [%]</td>
<td>-</td>
<td>+5.2</td>
<td>+5.6</td>
</tr>
<tr>
<td>Not at Front</td>
<td>Volume on ship ([dm^3/event])</td>
<td>46.8</td>
<td>49.2</td>
<td>50.7</td>
</tr>
<tr>
<td></td>
<td>Percentage difference [%]</td>
<td>-</td>
<td>+5.1</td>
<td>+3</td>
</tr>
</tbody>
</table>

Looking at Table 4-1, and Figure 4-6 it can be seen that there is a small difference between the two starting position cases, for wind coming 200° off the portside bow. Looking at the SHIPICE grid there is almost no difference in the two cases. For more detail, the calculation was repeated with a smaller grid on the deck. For these finer grids, there are some small differences but not significant.

In Figure 4-7 an example of a model test with wind simulated from ahead of the ship, 180°,
is shown. From this picture there can be seen that a lot of spray is generated at the front of the ship. The spray at the sides will mostly land in the water instead of on the ship.

**Figure 4-7:** Visualisation of a spray on a model with the wind from the front, this experiment was done within MARIN.

For the case that the wind is coming from ahead (180°), see Table 4-2, and Figure 4-8. Here you can see large differences between the different steps and the 2 starting positions. Especially in the figures of the finer grid on deck. Comparing Figure 4-7 with Figure 4-8(b) and Figure 4-8(d), there can be concluded that Figure 4-8(d) looks more similar compared with the picture. Where most of the spray is divided over the front of the deck and not in one straight line.

From these two wind cases there can be concluded that the wind direction with respect to the
Table 4-2: Parameters from SHIPICE calculated with the data of Sapone (smooth bow, 180° wind).

<table>
<thead>
<tr>
<th>Starting point</th>
<th>Parameters</th>
<th>10 steps</th>
<th>20 steps</th>
<th>30 steps</th>
<th>40 steps</th>
<th>50 steps</th>
<th>60 steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>Volume on ship [dm³/event]</td>
<td>61.8</td>
<td>32.4</td>
<td>22.2</td>
<td>16.8</td>
<td>13.8</td>
<td>11.7</td>
</tr>
<tr>
<td></td>
<td>Percentage difference [%]</td>
<td>-</td>
<td>-47.4</td>
<td>-31.9</td>
<td>-23.7</td>
<td>-18.7</td>
<td>-14.1</td>
</tr>
<tr>
<td>Not at Front</td>
<td>Volume on ship [dm³/event]</td>
<td>59.4</td>
<td>29.7</td>
<td>20.1</td>
<td>15</td>
<td>12.3</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>Percentage difference [%]</td>
<td>-</td>
<td>-49.8</td>
<td>-33</td>
<td>-24.5</td>
<td>-19.1</td>
<td>-15.7</td>
</tr>
</tbody>
</table>

ship speed vector has a large influence on the spreading of the spray. In this case there was looked at the frigate hull form used by Sapone (Sapone, 1990). This hull form is very pointed. For the 180° wind case there is also looked at the Atlantic Kingfisher (Gagnon et al., 2009) which has a more blunted hull form, see Figure 4-9. There is a large difference in the shape of these two bows. Comparing the percentage differences per amount of starting positions of Table 4-2 and Table 4-3, the volumes at the Atlantic Kingfisher are converging to a final value, where the volumes for the frigate hull form of Sapone is still not converged. There can be concluded that the bow shape has much influence on the mesh dependency.

![Figure 4-9](image_url)

Figure 4-9: Visualisation of the two different bow shapes at station 21. δ is the bow shape angle.

Table 4-3: Parameters from SHIPICE calculated with the data of the Atlantic Kingfisher (180° wind).

<table>
<thead>
<tr>
<th>Starting point</th>
<th>Parameters</th>
<th>10 steps</th>
<th>20 steps</th>
<th>30 steps</th>
<th>40 steps</th>
<th>50 steps</th>
<th>60 steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>Volume on ship [dm³/event]</td>
<td>121.5</td>
<td>99.6</td>
<td>90.6</td>
<td>86.4</td>
<td>84.6</td>
<td>82.2</td>
</tr>
<tr>
<td></td>
<td>Percentage difference [%]</td>
<td>-</td>
<td>-18</td>
<td>-9</td>
<td>-4.6</td>
<td>-2.1</td>
<td>-2.8</td>
</tr>
<tr>
<td>Not at Front</td>
<td>Volume on ship [dm³/event]</td>
<td>133.8</td>
<td>100.5</td>
<td>90.6</td>
<td>86.1</td>
<td>82.8</td>
<td>80.1</td>
</tr>
<tr>
<td></td>
<td>Percentage difference [%]</td>
<td>-</td>
<td>-24.9</td>
<td>-9.9</td>
<td>-5</td>
<td>-3.8</td>
<td>-3.3</td>
</tr>
</tbody>
</table>

For the 200° wind case it does not matter how much steps or which starting position there are taken. But looking at the Sapone 180° wind case there are large differences, even with 6 starting positions. These large differences are caused by the very pointed hull form. For the Atlantic Kingfisher there are only large differences between 10 and 20 starting positions, see Table 4-3. Where most hull forms are less pointed than the frigate hull form used in the
experiments of Sapone.

Throughout the thesis the following cases are used, based on the droplet distribution on the ship and the simulation time:

- 20 steps on the deck edge;
- A starting position not exactly at the front point of the ship.

Although the amount of used steps on the deck edge is questionable for the 180° wind case. The used amount of steps should depend on the bow shape and the bow shape angle ($\delta$). How smaller the angle how more steps needed to be used.

4-3 Hit Area Intensity distribution

For the determination of the Hit area intensity distribution the ship is divided in 42 different parts, based on the 21 sections and port and starboard of the ship, see Figure 4-4. It is assumed that the ship only exists out of horizontal and vertical plates, where the vertical plates will represent the sides of a deck structure for example and the horizontal plates will mainly represent the deck or the top of the deck structure.

Due to the ship motions it can be assumed that the amount of water of a certain part can be uniformly distributed over the total area of that part. The amount of water on that area will spread out. Also, the deck of the ship will have a small downward slope from the mid of the ship due to the camber, which is included in Eq. (2-37).
Chapter 5

Verification of the code

5-1 Trajectory

For the verification of the droplet trajectory, the NASA flight equations with drag (NAS) where used, using a simple 2D case. For the verification there is used a droplet diameter of 5 mm, a drag coefficient of 0.4 and starting x- and z-velocities of both 10 m/s. Calculating the maximum height of the droplet and the time needed to come to this highest point.

\[ y_{\text{max}} = \frac{V_t^2}{2g} \ln \frac{V_t^2 + Vl^2}{Vl^2} \]  \hspace{1cm} (5-1)

\[ t_{v=0} = \frac{V_t}{g} \tan^{-1} \left( \frac{V_z}{V_t} \right) \]  \hspace{1cm} (5-2)

Figure 5-1: Graph of the trajectory path of the droplet within time, the determined values are from the point at the black dot.
where \( V_t \) is the terminal velocity of the droplet:

\[
V_t = \sqrt{\frac{2mg}{CdA\rho_a}}
\]

With the given values, the maximum height is 3.077 m and the droplet got to this height in 0.731 s. With the model the max. height is determined at 3.076 m (just before the top of the trajectory), it took 0.717 seconds to come to this height. From this was concluded that the ballistic equation was correctly implemented.

### 5-2 Droplet cooling

To verify the droplet cooling equation a few simple first principle assumptions are made. These have to be true if the droplet cooling process is correctly simulated in the model:

- The droplets cannot be colder than the air temperature \( (T_d \geq T_a) \);
- The smaller droplets will be colder than the larger droplets;
- The droplets with a longer trajectory time will become colder than the ones with shorter trajectory time.

![Figure 5-2: Droplet temperature development during flight, with three different droplet diameters. Comparison with the equation of Kulyakhtin (2014) (a) and SHIPICE(b).](image)

In the SHIPICE model this is correctly modelled. Next to this check the model was compared with the analysis of droplet temperature evolution from Kulyakhtin (2014). Kulyakhtin looked at the droplet temperature evolution of 3 different droplet diameters (83, 260 and 920 µm) over 3 seconds. With an initial droplet temperature of -1°C, air temperature of -15°C, wind speed of 10 m/s and a relative humidity of 70%. In Figure 5-2 the droplet cooling of Kulyakhtin and the model are compared. There is small difference in the droplet temperature, which is best seen for the largest droplet size (green line). The difference may be caused by a small difference in the air and water properties \( (c_w, \rho_w, k_w, Pr, \nu_a, \rho_a, l_v, D_w, Sc \text{ and } \varepsilon) \). For this study these were realistically chosen but the were not specified in the model of Kulyakhtin. Also in the model the radiative heat flux of the droplet is included, Eq. (2-17), and Kulyakhtin does not include this heat flux. But the radiative heat flux has a minor influence in the cooling of the droplets.
5-3 Freezing equations with Horjen 2015

In the article of Horjen (2015), he looked at the difference of continuous and periodic icing with different air temperatures on a vertical cylinder. Most of the used parameters used in ICEMOD2.1 are given in the article, Table 5-1. For the determination of the heat transfer coefficient he used the Nusselt number for a cylinder, Eq. (2-26). In Figure 5-3 the icing intensity rate of Horjen is compared with SHIPICE. After comparing the icing intensity, also the total accreted ice mass ($g/m^2$) is compared with values of Horjen (2015). The data from Horjen (2015) is based on the icing intensity at the stagnation line ($\phi = 0$) of the incoming wind flow, which has not the highest icing intensity at the cylinder. Because there are two different air temperatures to compare the icing intensity with, there should also be two different droplet temperatures. But in the article only the droplet temperature for -12°C is reported, which is 2.2°C. That is why the used droplet temperature will also be 2.2°C for -8°C.

**Figure 5-3**: The icing intensity of the spray [$g/m^2s$] at the stagnation line and $Z=6.75$ m, (a) the ice intensity of Horjen’s paper, (b) the ice intensity of SHIPICE.

**Figure 5-4**: The accreted ice mass of the spray [$g/m^2s$] at the stagnation line and $Z=6.75$ m, (a) the ice mass of Horjen’s paper, (b) the ice mass of SHIPICE.

The difference of the icing intensity rate between Horjen and the SHIPICE model (Figure 5-3), for the first couple of periods is caused due to a difference in the salinity of the water film layer, see Figure 5-5. Best seen for an air temperature of -12 degree. Where the water film salinity of Horjen is much higher in the first couple of periods, giving a lower freezing temperature and a larger decrease of the icing intensity during these periods.
Table 5-1: Used known parameters in the freezing model with of Horjen (2015).

<table>
<thead>
<tr>
<th>Used parameters</th>
<th>Value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter column</td>
<td>5 m</td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>-8, -12 °C</td>
<td></td>
</tr>
<tr>
<td>Sea temperature</td>
<td>3 °C</td>
<td></td>
</tr>
<tr>
<td>Droplet temperature</td>
<td>2.2 °C</td>
<td></td>
</tr>
<tr>
<td>Salinity</td>
<td>34 ppt</td>
<td></td>
</tr>
<tr>
<td>Spray mass flux (cont.)</td>
<td>2.33 g/m²s</td>
<td></td>
</tr>
<tr>
<td>Median droplet diameter</td>
<td>3.8 mm</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>100 kPa</td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Significant wave height</td>
<td>5 m</td>
<td></td>
</tr>
<tr>
<td>Spray period</td>
<td>8.30 s</td>
<td></td>
</tr>
<tr>
<td>Single spray</td>
<td>2.56 s</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>21 m/s</td>
<td></td>
</tr>
</tbody>
</table>

5-3-1 Other Verification

Next to the comparison with Horjen (2015), there are some extra verifications steps for the total SHIPICE model.

- If the air temperature is above the freezing temperature of the water film, there should be no ice growth.
- The ice accretion rate can not be larger than the spray flux at that area part.

In the SHIPICE model there are made some adjustments to prevent these two cases to happen.
Chapter 6

Summary of results and discussions

6-1 Introduction

In this chapter the results of the SHIPICE model are presented and will be validated with previous experiments and models. This will be done in two parts: (1) the droplet distribution over the ship and (2) the icing events. Eventually the found results will be analysed and discussed.

6-2 Spray trajectories and volumes validation

Computations were carried out for the frigate hull form investigated by Sapone (1990). Sapone did model tests on the amount of spray and spray coverage on the main deck in regular waves. For his test he used a surfactant to reduce the tow tank water-surface tension, but it may still be assumed that scale effects are significant (Sapone, 1990). During these tests, Sapone simulated a ship speed of 18.4 knots, a wave height of 6 m and 3 different relative wind directions: 0°, 7.5°, and 15° with a relative wind speed of 51 knots. In the SHIPICE model these directions are 180°, 187.5°, and 195° (Figure 2-3(b)). In this case the ‘real’ (earth bound) wind speeds are 33.6 (15° wind) and 32.6 (0° wind) knots. The resulting wind direction with respect to the ship, for 15° is 23.2°, which is just off the port-side bow.

Sapone determined the spray distribution by including a two inch square grid system on the ship model. Each two inch square cell was assigned a value of 0 to 4, depending on the severity of the wetness on the deck. The 0 to 4 wetness scale has the following representation:

- **0** No wetness.
- **1** 1 to 24% of cell area slightly wetted.
- **2** 25 to 60% of cell area wetted slight to medium.
- **3** 61 to 99% of cell area wetted medium to heavy.
- **4** 100% of cell area medium to heavily wetted.
In the next Figures the data of the experiments of Sapone are compared with the data from SHIPICE. 4 different cases are analysed: first there was looked at two different bow shapes. Giving a conventional smooth bow and a knuckled bow (Figure 6-2). These two bows where tested with two different wind directions: $0^\circ$ and $15^\circ$. For these cases the spray at the deck edge was spread over 20 steps per station and at the bow (station 21) the first point was off the centre line of the ship.

**Figure 6-2:** Visualisation of a conventional smooth (a) and a knuckled (b) bow.

### 6-2-1 Smooth 35 bow

In Figure 6-3 and Figure 6-4 the location of the droplets and their intensities on the deck of the ship are shown compared with the wetting distribution from experiments of Sapone. In Table 6-1 the parameters are shown which are developed from the model, both with a linear and a Gaussian z-velocity distribution (Section 4-2-1). The data from Sapone was converted to a real size ship with a scale factor of $36^3$. The percentage on the ship in the tables is calculated with the total amount of water going up at the deck edge (15 tonnes/event) compared with the total amount of water falling on the ship.

### 15 degree wind

From Figure 6-3, Figure 6-4 and Table 6-1 it can be seen that the Gaussian and linear z-velocity distribution have almost the same intensity distribution on the ship. There can be seen that the spray collected on Sapone’s ship has its largest intensity more to the front of the ship compared with SHIPICE. This difference is probably because Sapone put 'spray root
Figure 6-3: Linear drop velocity distribution: area Intensity distribution for experiment Sapone smooth bow with 15 degree wind (a), model with a grid of 1.75x1.75 (b), model with SHIPICE grid (c) and drops (d).

Figure 6-4: Gaussian drop velocity distribution: area Intensity distribution for experiment Sapone smooth bow with 15 degree wind (a), model with a grid of 1.75x1.75 (b), model with SHIPICE grid (c) and drops (d).

devices’ on the port side of his model. The spray root devices were put on the bow of the ship as a sort of turbulence stimulators. The devices were made of plastic strips of 7.62 x
Table 6-1: Parameters from the model for the 35 smooth bow compared with the known data from Sapone, wind is 15 degrees.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sapone</th>
<th>Model (Linear)</th>
<th>Model (Gaussian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage on ship [%]</td>
<td>-</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/s]</td>
<td>13.7</td>
<td>16.4</td>
<td>16.3</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/event]</td>
<td>41</td>
<td>49.1</td>
<td>48.9</td>
</tr>
</tbody>
</table>

1.42 x 0.48 cm. These strips are quite thick and caused water streams to run up straight to the edge of the ship instead of following the natural stream of the water along the ship. The strips where located between station 19 and 20, see Figure 6-5. The effect of these strips are seen best in Figure 6-7(a), where the wind was coming from the front. Further explanation about the effect of these strips are done in the 0 degree wind case.

In the following sections the experiments of Sapone will only be compared with the model with a linear z-velocity distribution, because there is seen almost no difference with the Gaussian distribution.

Another interesting outcome of the trajectory path is the amount of droplets on the deck, see Figure 6-6. From this graph there can been seen that the smaller droplets are dominant in landing on the ship, although the largest contribution for the total weight that goes up at the edge has a droplet mean diameter around 70 mm. Most of the droplets landing on the deck have a diameter below 20 mm. This difference in droplet sizes is due to the shape of the ship, which throws the larger droplets aside the ship. Where only the smaller droplets are influence by the wind in the ballistic process.

All the previous icing models were using droplet sizes between 0.5 and 2 mm. Looking at Figure 6-6 there can been seen that this is not the case in SHIPICE, where the largest contribution of the droplets is laying between 1 and 16 mm. In SHIPICE a droplet size distribution functions is adopted by Aalbers and Poen (2015), that is why in this model there are multiple droplets size with a larger range. In previous icing models they are assuming that only the slamming events (see Section 2-2-1) have a large contribution for icing. From Figure 6-6 there can be concluded that this is not the case and that the larger droplets should also be taken into account. Currently there are still some uncertainties about the droplet size distribution function, further research about this process is currently be done by H. Eikelboom, a Master student at the Technical University Delft. Because in the model there are taken droplet size steps of 5 mm, there is a strange peak in the beginning of the blue line.
in Figure 6-6. Due to this size step the droplets go from 1 mm straight to 6 mm, not knowing what would be the amount of droplets in between. Also in this figure there can be concluded that there is almost no difference between the Gaussian and linear z-velocity distribution.

0 degree wind

In Table 6-2 there can be seen that the volume at the front of the ship in the model is higher than in the experiments of Sapone. This large difference is caused by the chosen amount of starting positions. If there were taken 60 steps instead of 20, the amount of volume landing on the ship would be 10.2 $dm^3/event$ as mentioned in Chapter 4.

**Table 6-2:** Parameters from the model for the 35 smooth bow compared with the known data from Sapone, wind is 0 degree.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sapone</th>
<th>Model (Linear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage on ship [%]</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/s]</td>
<td>1.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/event]</td>
<td>4.7</td>
<td>29.7</td>
</tr>
</tbody>
</table>

The difference in Figure 6-7(a) between port and starboard side is caused by the spray devices, mentioned for the 15 degree wind case. At the portside of the bow there is a high intensity between station 19 and 20, exactly at the positions where Sapone put the spray devices. At
the starboard side there can be seen that at these location there is not a high intensity. But probably the starboard side will give a too low assumption of the volume per area. That is the reason why Sapone put the spray devices on the model, to get a better assumption of the volume landing on the ship.

![Figure 6-7: Linear drop velocity distribution: area Intensity distribution for experiment Sapone smooth bow with 0 degree wind (a), model with a grid of 1.75x1.75 (b), model with SHIPICE grid (c) and drops (d).](image)

6-2-2 Knuckled 35 bow

In Section 6-2-1 it was mentioned that the total amount of water going up to the deck edge is 15 tonnes/event, for the knuckled bow this is 17 tonnes/event.

15 degree wind

**Table 6-3:** Parameters from the model for the 35 knuckled bow compared with the known data from Sapone, wind is 15 degree.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sapone</th>
<th>Model (Linear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage on ship [%]</td>
<td>-</td>
<td>0.25</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/s]</td>
<td>101.9</td>
<td>14.5</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/event]</td>
<td>305.6</td>
<td>43.5</td>
</tr>
</tbody>
</table>

Just as for the smooth bow the highest intensity of the droplets lay further too the front with the experiments of Sapone, due to the spray root devices. Looking at Table 6-3 the amount of spray at the front of the ship by SHIPICE is 10 times lower than the amount of spray determined by Sapone. This large difference is caused by the spray root devices on the
knuckled bow of Sapone. These strips are going over the knuckled, leading also the spray over the knuckled. Now the outward end velocity of the spray is based on the angle of the knuckled part and not on the angle below the knuckle. Where in the SHIPICE model the spray is mainly influenced by the angle below the knuckle.

To determine what the influence is of these strips, they are modelled into the SHIPICE model, for station 20 and 19. Assuming that the velocity in the x-direction will not be affected by the ship’s velocity and that the velocity in the y-directions is based on the knuckle angle.

Table 6-4: Parameters from the model for the 35 knuckled bow compared with the known data from Sapone, wind is 15 degree. Strips were simulated in the model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sapone</th>
<th>Model (Linear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage on ship [%]</td>
<td>-</td>
<td>1.12</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/s]</td>
<td>101.9</td>
<td>63.8</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/event]</td>
<td>305.6</td>
<td>191.5</td>
</tr>
</tbody>
</table>

Table 6-5: Parameters from the model for the 35 smooth bow compared with the known data from Sapone, wind is 15 degree. Strips were simulated in the model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sapone</th>
<th>Model (Linear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage on ship [%]</td>
<td>-</td>
<td>0.18</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/s]</td>
<td>13.7</td>
<td>8.8</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/event]</td>
<td>41</td>
<td>26.5</td>
</tr>
</tbody>
</table>

Table 6-4 shows that the strips have a large influence on the amount of water that will land
on the ship. Comparing the volume measured by Sapone and the calculated volume with the strips lays now in the right order of magnitude. For the influence of the strips on the smooth bow, see Table 6-5. These two tables show that the strips have a very large influence for the knuckled bow, but not for the smooth bow. This large difference is caused due the droplet velocity in the y-direction, which is now influence by the knuckle angle. On a real size ship without strips, the spray will not follow the direction of the knuckled, but will separate from the bow at the location where the knuckle starts. Unfortunately, there is no spray data available on real sized ships.

Due to the comparison with the strips, there can be conclude that for the knuckled bow these strips have a very large influence. Probably SHIPICE models the knuckled bow correctly, but it is recommended to have a detailed study of the knuckled bow without strips on the bow.

0 degree wind

![0 degree wind](image)

**Figure 6-9:** Linear drop velocity distribution: area intensity distribution for experiment Sapone knuckled bow with 0 degree wind (a), model with a grid of 1.75x1.75 (b), model with SHIPICE grid (c) and drops (d).

**Table 6-6:** Parameters from the model for the 35 knuckled bow compared with the known data from Sapone, wind is 0 degree.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sapone</th>
<th>Model (Linear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage on ship [%]</td>
<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/s]</td>
<td>25.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Volume on ship [dm$^3$/event]</td>
<td>76.5</td>
<td>25.4</td>
</tr>
</tbody>
</table>

The amount of volume landing on the ship is 3 times lower calculated with SHIPICE than the model test of Sapone. This difference is caused by strips on the knuckled bow of Sapone,
which will give much more spray landing on deck.

6-2-3 Discussion smooth and knuckled bow spray generation

Comparing the volumes on the smooth and knuckled bow, the first thing that can be concluded is that the knuckled bow generated a lot more spray in Sapone’s experiment than was calculated with SHIPICE. This difference is probably caused because the knuckled bow is influence by the spray root devices on the bow of Sapone. Probably SHIPICE models the knuckled bow correctly, but it is recommended to have a detailed study of the knuckled bow without strips on the bow. For the smooth bow the results lay in the right order of magnitude.

For both cases with 15 degree wind the spray modelled with SHIPICE will land further away from the front of the ship than in the experiments of Sapone. This difference is probably caused by the spray root devices attached on the model ship of Sapone. Therefore, the end-location of the spray on deck should be investigated further.

6-3 Icing validation

For the icing validation the SHIPICE model will be validated with two different icing cases: (1) an icing event on the Norwegian Coast Guard vessel KV Nordkapp hitting a Polar Low on the 26th of February 1987 in the Barents Sea (Samuelsen et al., 2015) and (2) an icing event on the Atlantic Kingfisher on 29 December 2006, east of St. John’s (Bruce; Gagnon et al., 2009).

6-3-1 KV Nordkapp

During this trip measurements were taken every 3 hours. For the salinity, relative humidity, and air and sea temperature the averaged between two observing time steps were taken. For all the observed met-ocean data see Samuelsen et al. (2015). The direction of wind and waves is for this study re-defined in the ship-bound system of coordinates. In Table 6-7 the used parameters for the model are shown. Because the polar low started around 17 hr, the time
The icing measurements on the KV Nordkapp were taken at a fixed position on an almost vertical plate (85° tilt). This plate was located 19.7 m from the front of the ship, with a width of 4 m (-2 m < y < 2 m) and the height was going from the main deck to the canon deck (0 m < z < 3 m). SHIPICE computes for larger areas, in this case the total area of the front of the deck house. The comparison is made by taking an average over the ice growth on portside and starboard. However, there are large difference between the spray fluxes, spray temperature and calculated icing rates for portside and starboard, see Table 6-8. The averaged of these two measured data can be found in Table 6-9. Also they measured a total ice load of 110 tons during the 17 hours icing event. In Table 6-9 the observed total ice load is 6.5 tonnes/hr, the average of 110 tons in 17 hours. Not knowing what the exact overall ice accretion rate per hour was. The ice load was observed based on readings of the draft/ballast water.

Table 6-8: Result on the measured area calculated with SHIPICE for five different time intervals, for the sea temperature modeled with the ocean model. These are the results for the starboard and portside of the front of the deck house.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>6-9 hr</th>
<th>9-12 hr</th>
<th>12-15 hr</th>
<th>15-17 hr</th>
<th>17-18 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray flux [kg/m²s] SB</td>
<td>0.22</td>
<td>0.48</td>
<td>0.47</td>
<td>0.15</td>
<td>1.59</td>
</tr>
<tr>
<td>Droplet Temperature [°C] SB</td>
<td>-0.33</td>
<td>-2.7</td>
<td>-2.1</td>
<td>-2.63</td>
<td>1.15</td>
</tr>
<tr>
<td>Ice rate (SHIPICE) [mm/hr]</td>
<td>11.85</td>
<td>12.5</td>
<td>14</td>
<td>15.6</td>
<td>20.6</td>
</tr>
<tr>
<td>Spray flux [kg/m²s] PS</td>
<td>1.28</td>
<td>3.93</td>
<td>3.84</td>
<td>1.38</td>
<td>7.42</td>
</tr>
<tr>
<td>Droplet Temperature [°C] PS</td>
<td>-1.48</td>
<td>0.61</td>
<td>-0.13</td>
<td>-4.72</td>
<td>0.68</td>
</tr>
<tr>
<td>Ice rate (SHIPICE) [mm/hr]</td>
<td>12.2</td>
<td>11.3</td>
<td>12.6</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

Discussion KV Nordkapp

In Figure 6-11 the total weight per droplet size are shown for the two different wave/wind directions: 200° and 210°. There can be seen that there should be taken more than one droplet size into account. If the heading is coming more from ahead, the range of droplets landing on the ship becomes larger, but the total volume on the ship becomes lower.
Table 6-9: Averaged result on the measured area calculated with SHIPICE for five different time intervals, for the sea temperature modeled with the ocean model. The last two rows are the total amount of ice for the total ship.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>6-9 hr</th>
<th>9-12 hr</th>
<th>12-15 hr</th>
<th>15-17 hr</th>
<th>17-18 hr</th>
<th>tot. 12 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray flux ([kg/m^2s])</td>
<td>0.75</td>
<td>2.21</td>
<td>2.16</td>
<td>0.77</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>Droplet Temperature (\degree C)</td>
<td>-1.31</td>
<td>0.24</td>
<td>-0.34</td>
<td>-3.67</td>
<td>0.92</td>
<td>-</td>
</tr>
<tr>
<td>Ice rate (SHIPICE) ([mm/hr])</td>
<td>12.03</td>
<td>11.9</td>
<td>13.3</td>
<td>16.3</td>
<td>18.8</td>
<td>-</td>
</tr>
<tr>
<td>Ice rate (Observed) ([mm/hr])</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>Average ice load (Observed) ([tonnes/hr])</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>78</td>
</tr>
<tr>
<td>Ice load (SHIPICE) ([tonnes/hr])</td>
<td>5.31</td>
<td>9.71</td>
<td>11.47</td>
<td>4.48</td>
<td>26.36</td>
<td>114.8</td>
</tr>
</tbody>
</table>

Figure 6-11: Comparison with the total weight per droplet diameter landing on the ship (blue & green) and the total weight per droplet diameter going up at the edge of the ship (red).

In Table 6-8 small differences are found between portside an starboard at the deck house front. This is explained as follows. In Figure 6-12 the ice thickness on the front of the deck house for the 17-18 time interval is shown. At point 1 in the graph there is coming a new spray on the ship. Between 1 and 2 the spray causes a thermal break-off of the ice layer, due to a higher spray temperature than the freezing temperature of the water film. At point 2 the spray stopped. Between 2 and 3 the ice thickness can grow again, due to no negative effect of the spray. The spray flux for the starboard and portside are 1.6 and 7.4 \(kg/m^2s\), respectively, and the spray temperature on the portside is 0.7\(\degree\)C and on the starboard side it is 1.2\(\degree\)C. This will give a larger thermal break-off on the portside due to the large spray flux, which is also shown in Figure 6-12.

The observed metocean icing data where measured once in the 3 hours. For the SHIPICE model there were taken averaged values for these 3 hours. Meaning that the mean icing rate at the KV Nordkapp is also an averaged. But this is the best value that can be determined.

The observed icing rates at several time intervals are zero. In the SHIPICE model there are no icing rates determined that are zero. But there is some thermal break-off after a spraying event, see Figure 6-12. Other causes of break-off due to e.g. spray impact were not
considered in the model. The observed icing growth is taken close to the centreline of the ship. Comparing that with the average of SHIPICE values for portside and starboard may not be accurate enough due to the non linear effect of influx temperatures.

The visually estimated wave height and wave period by the crew are not for every time step a good estimation. In the paper of Samuelsen et al. (2015) the wave height at 6:00 was estimated to be 7.5 m. But compared with the other observed wave heights and the fact that it was dark during the observation, there was used a significant wave height of 6 m instead, for the 6-9hr time interval. Also the time step of 15-18 hr was divided in two parts. Because the polar low started at 17:00 and it would not be a good representation to take the averaged value between 15:00 and 18:00 hour.

From Table 6-9 there can been seen that for the same area on the ship the different time intervals have different droplet temperatures. A part of this difference in temperature is caused by the air temperature. However, in the 15-17 hr and 17-18 hr time interval the air temperature is constant, -17.35°C, but the droplet temperature is not the same. This difference is caused by different droplet sizes. When falling on the deck, the smaller droplets have the coldest droplet temperature. Also, the trajectory time has an influence on the droplet temperature, which is influenced by the wind heading and the start location of the droplets at the edge of the ship. From this may be concluded that the droplets in the time interval of 15-17 hr have smaller droplet sizes compared with 17-18 hr and are less affected by the wind, which increased from 15 to 25 m/s.

From Table 6-8 there can be seen that for the time-intervals of 9-12 and 12-15 the droplet temperature is lower on the starboard side, where in the other time intervals the droplet temperature is lower on the portside. Looking at Table 6-7 there can be seen that for these two time-intervals the wind and wave direction is 210 instead of 200 for the other time intervals. With this wind/wave direction there will blown more smaller droplets to the starboard side, giving a smaller droplet temperature for the starboard side. Comparing the spray flux of 6-9hr and 9-12hr, it is almost doubled for the 9-12hr time-interval. These time intervals have the same ship velocity, meaning that the larger spray flux is mostly caused due to the different

**Figure 6-12:** Graph of the ice thickness on the front of the deck house on the KV Nordkapp for the 17-18 time interval, for starboard and portside. It shows the first 10 spray periods.
SHIPICE is not including the effect of snow, fog, rain and wind-generated spray in the model. The water amount of the contribution of these effects are not available for this study, that is why it is not included in the model. Also on the measurement moments on the KV Nordkapp they only considered sea spray and fog as icing cause, although during the whole trip there where some snow showers.

In the last two rows of Table 6-9 the total ice load per hour for the total ship is determined. For Table 6-9 the total amount for 12 hours is 115 tonnes. This value is calculated separately for their time intervals (uncorrelated). Calculating them correlated the amount of ice on the ship would be 114. The correlation between time steps is obtained by taking the end value of the previous time interval as starting point for the next time interval. The icing in the correlated calculations is a little lower because the dry deck has air temperature and the iced surface has the freezing temperature of the water film, which is higher than the air temperature. These values lay quite close to the 110 tonnes in 17 hours. There are two main reasons that the calculated value would probably be a little higher than the observed 110 tonnes for 17 hours: (1) The heat input from the living-quarters on the ship, which will melt some ice and (2) The methods ignores vertical air flows around the ship geometry, which affects details of spray influx (Kulyakhtin, 2014).

Figure 6-13: Observed and calculated ice thickness. The ModStall algorithms are based on calculations of Stallabrass and the Test model, is a model developed in Samuelsen et al. (2015). Further explanations about these models (except SHIPICE) can be found in Samuelsen et al. (2015).

In Figure 6-13 the observed ice thickness on the KV Nordkapp is compared with SHIPICE, ModStall and a test model algorithm developed by Samuelsen et al. (2015). There can be seen that SHIPICE lays in the right range of quantity compared with the observed data. Calculations of ModStall and the 'test model' are significantly higher than the observed data, while values from other models as shown in the paper by Samuelsen et al. (2015) would not fit on the same page here. At 17 hr the polar low starts. At this point the wind velocity goes up from 15 to 25 m/s, giving a larger ice growth rate. The total observed ice thickness in the time interval of 6-18hr is 12 cm. The calculated ice thickness with SHIPICE for the
front of the deck house is 16 cm. This value is slightly higher compared with the observed ice thickness. The mean difference is that the moment of the ice growth is different with the observed thickness, see Figure 6-13. Why there was no ice growth observed on the front of the deck house between 9 and 15 hours is unknown. There was observed ice growth on the total ship during this time interval. Because SHIPICE is using the averaged data of two data points, this is a good estimation. Not knowing what has happened in between two observed data points.

Comparing the amount of icing on the KV Nordkapp calculated with SHIPICE and with the ModStall and Test model, there is a difference in the icing rate. There are two main reasons for this: (1) in ModStall and Test model they are using an constant droplet temperature of -2.5 °C, where SHIPICE is having droplet temperatures between -4.45 and 1.57 °C (depending on the time interval). (2) In ModStall and Test model they are using a spray flux of around 0.055 kg/m²s, where SHIPICE is having a spray flux between 0.15 and 7.4 kg/m²s (depending on the time interval).

6-3-2 Atlantic Kingfisher

The second validation case is for the Atlantic Kingfisher supply vessel, returning from the Hibernia oilfield platform to St. John’s, Canada. The observed icing rate and thickness of the Atlantic Kingfisher is determined with a Marine Icing Monitoring System (MIMS). The MIMS is a visual based technique for monitoring marine ice accumulations, with high-resolution digital cameras. For further explanation about the MIMS see the paper of Gagnon et al. (2009). They did local measurements on deck structures at the front of the ship, see Figure 6-14. In this report comparisons are made for position 12 till 17.

SHIPICE is designed to look at a large area on the ship and not at small structures on deck, as was done on the Atlantic Kingfisher. For the comparison it will be assumed that the local measurements are representative of the icing growth over a larger area (sections of the ship, portside and starboard). Where position 14 and 15 lay on station 21, position 16 on station 20, position 17 on station 19 and position 12 and 13 on station 18, all on the starboard side of the ship.

The observed and logged voyage data are from the ship log, provided privately from R. Gagnon. The last 3 parameters in Table 6-10 were not given, but are an estimation of these parameters for the location near St. John’s in December.

| Table 6-10: Used trip data of the Atlantic Kingfisher, for different time intervals. |
|-----------------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Parameters                        | 8-9 | 9-11 | 11-13 | 13-15 | 15-17 | 17-19 | 19-21 | 21-23 | 23-01 |
| Ship velocity [m/s]                | 2.06 | 2.16 | 1.6  | 1.6  | 1.5  | 1.9  | 1.65 | 2.1  | 1.9  |
| Wind velocity [m/s]                | 18.9 | 18.9 | 18.9 | 18.9 | 18.9 | 17.17| 15.5 | 15.5 | 15.5 |
| Direction [°degree]                | 200  | 210  | 210  | 200  | 180  | 180  | 180  | 180  | 180  |
| Significant wave height [m]        | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    |
| Air Temperature [°C]               | -3   | -3   | -3   | -2   | -4   | -5   | -6   | -6   | -6   |
| Relative Humidity [%]              | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  | 0.8  |
| Salinity [ppt]                     | 35   | 35   | 35   | 35   | 35   | 35   | 35   | 35   | 35   |
| Sea Temperature [°C]               | 3    | 3    | 3    | 3    | 3    | 3    | 3    | 3    | 3    |
In the paper of Gagnon et al. (2009) it is mentioned that the images were acquired during daylight and that they measured for 8 hours, starting in the morning. In the extended paper of Bruce a larger time period was considered, max. 13 hours. The observed ice rate in Table 6-11 are based on the values in Bruce. The observed ice rate per time interval will start at 8 hr, although in the papers of Gagnon et al. (2009) and Bruce not the exact time of the observed ice thickness was mentioned.

Figure 6-14: Locations on the front of the deck of the Atlantic Kingfisher where the MIMS measured the icing thickness.

Table 6-11: Results calculated with SHIPICE for the Atlantic Kingfisher, for the different stations.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spray flux [kg/m²s]</td>
<td>1.91</td>
<td>2.19</td>
<td>2.18</td>
<td>1.5</td>
<td>1.47</td>
<td>1.21</td>
<td>0.88</td>
<td>1.14</td>
<td>1.04</td>
<td>1.5</td>
</tr>
<tr>
<td>21</td>
<td>Spr. Temp [°C]</td>
<td>2.95</td>
<td>2.95</td>
<td>2.94</td>
<td>2.96</td>
<td>2.95</td>
<td>2.93</td>
<td>2.89</td>
<td>2.9</td>
<td>2.89</td>
<td>2.93</td>
</tr>
<tr>
<td></td>
<td>Ice rate (SHIPICE) [mm/hr]</td>
<td>3.87</td>
<td>4.12</td>
<td>3.59</td>
<td>0.0</td>
<td>5.94</td>
<td>7.67</td>
<td>8.86</td>
<td>9.01</td>
<td>8.97</td>
<td>5.78</td>
</tr>
<tr>
<td></td>
<td>Ice rate (Observed, 14) [mm/hr]</td>
<td>12.5</td>
<td>7</td>
<td>-5.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Ice rate (Observed, 15) [mm/hr]</td>
<td>-4</td>
<td>5.5</td>
<td>24</td>
<td>7.5</td>
<td>16.5</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.8</td>
</tr>
<tr>
<td>20</td>
<td>Spray flux [kg/m²s]</td>
<td>0.72</td>
<td>1.07</td>
<td>1.03</td>
<td>0.67</td>
<td>0.5</td>
<td>0.4</td>
<td>0.36</td>
<td>0.34</td>
<td>0.33</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Spr. Temp [°C]</td>
<td>2.92</td>
<td>2.91</td>
<td>2.9</td>
<td>2.93</td>
<td>2.91</td>
<td>2.88</td>
<td>2.82</td>
<td>2.82</td>
<td>2.82</td>
<td>2.88</td>
</tr>
<tr>
<td></td>
<td>Ice rate (SHIPICE) [mm/hr]</td>
<td>4.04</td>
<td>3.88</td>
<td>3.72</td>
<td>0.0</td>
<td>6.13</td>
<td>7.77</td>
<td>8.41</td>
<td>9.04</td>
<td>8.9</td>
<td>5.81</td>
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<td>Ice rate (Observed, 16) [mm/hr]</td>
<td>4.5</td>
<td>1</td>
<td>4</td>
<td>11</td>
<td>4.5</td>
<td>6.5</td>
<td>8.5</td>
<td>-</td>
<td>-</td>
<td>2.7</td>
</tr>
<tr>
<td>19</td>
<td>Spray flux [kg/m²s]</td>
<td>0.52</td>
<td>0.81</td>
<td>0.79</td>
<td>0.44</td>
<td>0.37</td>
<td>0.29</td>
<td>0.19</td>
<td>0.21</td>
<td>0.19</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Spr. Temp [°C]</td>
<td>2.87</td>
<td>2.85</td>
<td>2.84</td>
<td>2.88</td>
<td>2.88</td>
<td>2.8</td>
<td>2.65</td>
<td>2.65</td>
<td>2.64</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>Ice rate (SHIPICE) [mm/hr]</td>
<td>4.08</td>
<td>3.95</td>
<td>3.76</td>
<td>0.0</td>
<td>6.1</td>
<td>7.68</td>
<td>8.55</td>
<td>8.82</td>
<td>8.68</td>
<td>5.74</td>
</tr>
<tr>
<td></td>
<td>Ice rate (Observed, 17) [mm/hr]</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>0.5</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.4</td>
</tr>
<tr>
<td>18</td>
<td>Spray flux [kg/m²s]</td>
<td>0.49</td>
<td>0.57</td>
<td>0.56</td>
<td>0.47</td>
<td>0.21</td>
<td>0.18</td>
<td>0.1</td>
<td>0.14</td>
<td>0.12</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Spr. Temp [°C]</td>
<td>2.83</td>
<td>2.8</td>
<td>2.75</td>
<td>2.85</td>
<td>2.74</td>
<td>2.69</td>
<td>2.41</td>
<td>2.45</td>
<td>2.43</td>
<td>2.63</td>
</tr>
<tr>
<td></td>
<td>Ice rate (SHIPICE) [mm/hr]</td>
<td>4.1</td>
<td>4.15</td>
<td>3.83</td>
<td>0.0</td>
<td>5.95</td>
<td>7.45</td>
<td>7.85</td>
<td>5.6</td>
<td>8.3</td>
<td>5.57</td>
</tr>
<tr>
<td></td>
<td>Ice rate (Observed, 12) [mm/hr]</td>
<td>20</td>
<td>1</td>
<td>3.5</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Ice rate (Observed, 13) [mm/hr]</td>
<td>2.5</td>
<td>7.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Figure 6-15: Graphs of the iced structure width, for position 16 and 17. The blue dots are the observed iced width according to Gagnon et al. (2009). The yellow dots are the calculated ice thickness, calculated with SHIPICE. All the dots have a second-order polynomial trendline. The 0 point in the graph is at 8hr.

Discussion Atlantic Kingfisher

In Figure 6-16 the total weight per droplet size are shown for the three different wave/wind directions: 180°, 200°, and 210°. Just as for the KV Nordkapp, there can be seen that there should be taken more than one droplet size into account. When there are head seas almost all the small droplets are not landing on the ship any more.

Figure 6-16: Comparison with the total weight per droplet diameter landing on the ship (blue, pink & green) and the total weight per droplet diameter going up at the edge of the ship (red).

Just as for the KV Nordkapp validation, SHIPICE used per 2 hr time interval constant input values for the MetOcean data, i.e. those taken at the start of each interval. In the logbook of C.M. Hoes Master of Science Thesis
the Atlantic Kingfisher also the precipitation was noted. Most of the time it was only cloudy but the last two time intervals had bits of rain. The atmospheric icing part of the ice growth is not taken into account in SHIPICE.

In Table 6-10 there can be seen that after time interval 13-15hr the wind/wave direction has changed from 200-210 degree to 180 degree (coming from ahead). In Table 6-11 it is shown that the spray flux for the last five time intervals is for every station lower than of the first four time intervals. Concluding from this, there will land more spray on the ship when the wind/wave direction is not coming exactly from the front.

For time interval 13-15hr the air temperature measured is -2 °C. This lays very close to the -1.9 °C, which is the freezing temperature of seawater with a salinity of 35 ppt. For all the positions SHIPICE calculated no ice growth during this time interval, due to the 'high' air temperature. After 15 hr it got colder, so the results of SHIPICE predict ice growth.

From Figure 6-15 for position 16 and 17 there can be seen that the observed ice growth declines if the position lays further away from the front of the bow. Looking at the calculated ice growth for these positions they are almost the same. Giving no difference for the station. SHIPICE give a too low ice thickness for position 16. Where for position 17 it is too high. Although the ice thickness is not exactly the same, they are laying in the right order of magnitude.

In Figure 6-17 a spraying event on the Atlantic Kingfisher is shown. in this picture there can be seen that there are only very fine droplets in the spray, most of them probably smaller than 1 mm (the smallest droplet size for the rapid immersion and slamming events in the SHIPICE model). Due to these small droplets the droplets will cool very quickly and if they will land on the small structures it will freeze down more easily. Looking at Figure 6-18 there is only icing on the deck structures and the higher located deck, but not on the main deck. This is caused by the larger droplets landing on the main deck which will have a higher temperature and spray flux, which will not easily freeze down with an air temperature of -3 °C. Where SHIPICE is looking at a large area and the positions on the Atlantic Kingfisher are rather small.

![Figure 6-17: Picture of the Atlantic Kingfisher during a spraying event, there can be seen that the droplets in the spray are small. Figure 6-18: Picture of the Atlantic Kingfisher with a small marine icing accumulation on the front of the deck.]
6-3-3 Discussion Icing validation

First of all the icing case of the Atlantic Kingfisher is more difficult to validate with the SHIPICE model than the KV Nordkapp. This is because for the Atlantic Kingfisher they only measured at a few selected points on the ship where the KV Nordkapp looked at the icing rate for a large plate. SHIPICE is not intended to look at points or very small areas, because that level of detail is not in the hydrodynamic spray model and not in the geometry modelling.

Because the air temperature during the measurements on the Atlantic Kingfisher were between -2 and -6 °C, the icing rates at this ship are much smaller than those at the KV Nordkapp, which has an air temperature between -12 and -18 °C. Where SHIPICE works better with lower air temperatures, which lay not too close to the freezing temperature of the water film. Because than the large temperatures of the spray and their spray flux has less influence on the ice growth. SHIPICE is not developed for much detail, where the local effects of run-off and spray flux differences play no role.
This thesis presented an overview of marine icing processes, followed by methods to implement these in an icing prediction model (SHIPICE). The results were validated by comparing the SHIPICE model with observed data from voyages of the KV Nordkapp and the Atlantic Kingfisher. Also the possible effect of spray impact on the accreted ice is briefly discussed.

**SHIPICE, icing model**

During this thesis the SHIPICE icing model is developed. SHIPICE is the first marine icing model that includes different droplet sizes and velocities. The model was built in Matlab R2015a and uses as input a probabilistic sea spray generation model (Aalbers and Poen, 2015). Together with this sea spray generation model, the model is based on metocean data to determine the physical icing processes.

In previous icing models the spray fluxes are significantly small that they did not need to include the run-off heat flux. Where the calculated spray fluxes with SHIPICE are much larger. In the SHIPICE model the run-off heat flux cannot be neglected.

The deck in the SHIPICE model is divided in 42 different areas: starboard/port side and the 21 stations of the ship. There can exist a deck house on top of the deck, where the front, top and sides of the deck house are divided in the same way. For every area the spray flux and spray temperature are calculated. Eventually the ice thickness and ice growth per area will be calculated.

During the development of SHIPICE the model is compared with different experimental data. First the trajectory path was compared with model tests of Sapone (1990). Eventually the total SHIPICE model was compared with observed icing data of the KV Nordkapp and the Atlantic Kingfisher voyages.
Droplet trajectory

- The spray water influx intensities on the ship compared with those measured by Sapone lay further away from the front of the ship. This is partly caused by the spray root devices Sapone put on the hull of the model, between station 21 and 19. It may also be related to the adopted vertical droplet velocity distribution of the spray drops.

- SHIPICE is compared with the Sapone 15 degree wind case, for a linear and Gaussian vertical droplet velocity distribution. There is almost no difference between these two different velocity distributions. Also the amount of droplet sizes landing on the ship are almost the same for these two cases. There is not much known about this phenomenon, so for the other calculations a linear velocity distribution was used.

- The intensity distributions of the smooth bow are in the right order of magnitude compared with the experiments of Sapone. For the knuckled bow however SHIPICE computed 10 times less water on the deck compared with Sapone’s measurements. This is caused by the spray root devices going over the knuckled bow. Probably the obtained values with SHIPICE for the knuckled bow lay in the right order of magnitude compared with a real sized ship.

- In Figure 6-6, Figure 6-11, and Figure 6-16 the droplet sizes landing on the deck are compared with the droplet sizes going up at the edge of the ship. In previous icing models the used droplet sizes were assumed between 0.5 and 2 mm. In the figures there can been seen that this is not correct and that all the droplet sizes should be considered.

Icing

- Comparing SHIPICE with ModStall and Test model the total spray flux and droplet temperature (for some time intervals) is much higher in SHIPICE. ModStall and Test model are only using a droplet size of 2 mm, which will cool much faster than the droplet size range used in SHIPICE. For the spray flux they are using a very simplified sea spray generation model, that is why there is a very large difference with the SHIPICE model.

- For the total amount of ice on the whole ship SHIPICE has calculated 115 tonnes in 12 hours. During the trip on the KV Nordkapp they observed 110 tonnes of ice in 17 hours. The amount calculated with SHIPICE do not include the heat input from the living-quarters on the ship, that is why it is a little higher than the observed value.

- The total observed ice thickness on the front of the KV Nordkapp in the calculated time interval (6-18hr) is 12 cm, where the calculated ice thickness with SHIPICE is 16 cm. The mean difference is that SHIPICE has ice growth at different moments in time compared with the observed ice growth. Furthermore SHIPICE is using the averaged observed data, not knowing what the metocean parameters were in between two data points. Although this difference it still has a good estimation, compared with the other icing models.

- The effect of a spray falling on an accreted ice layer can been seen in the SHIPICE model, see icing rates of KV Nordkapp (Figure 6-12). It shows that the heat influx from the incoming spray is important. If the spray temperature of the incoming spray is
higher than the water film temperature, it will decrease the ice thickness slightly. Other models were never able to capture these effects, due to too small droplet diameters and one droplet velocity.

- The icing event on the Atlantic Kingfisher was difficult to compare with SHIPICE. Because the air temperature during this icing event was between -2 and -6 °C, where the freezing temperature of the water layer has its maximum at -1.9 °C. Also the measurements were at small parts of the structure, where SHIPICE is designed to look at large areas. But even with these difficulties, SHIPICE was able to determined ice growth with an air temperature of -3 °C.

- The spray temperature landing on the ship is different per time interval. This difference is not only caused by the air temperature, but mainly depends on the droplet size and the trajectory time of the different droplets. In previous icing models it was difficult to determine the trajectory time. That is why there was not a good estimation of the droplets cooling during their trajectory. SHIPICE looks at every droplet class separately, calculating also the trajectory time for every droplet class.

SHIPICE is mainly developed to determine the ice growth and total amount of ice at relatively large areas on a ship. Where very detailed effects are ignored. These are especially seen when the conditions are close to the freezing temperature of the water film like in the case of the Atlantic Kingfisher voyage. Therefore SHIPICE works better with air temperatures not too close to the freezing temperature of the water film.

The development of SHIPICE will allow the users to dimension the amount of ice growing on particular areas on the ship, given the sea states and air temperatures. It could be a practical engineering method to predict the more severe icing situations. Also, it will provide an improved basis for regulations and guidelines in an Arctic environment.
Chapter 8

Recommendations

In the current model an assumption is made for the vertical component of the droplet velocity distribution. In Chapter 6 the difference between linear and Gaussian velocity distribution is discussed. The spray landing on the deck modelled with SHIPICE is generally a bit too far aft on the ship. This follows from comparison with the experiments of Sapone. It is recommended that this distribution is further investigated and defined, because it has influence on where the spray lands on the ship.

The amount of water landing on the knuckled bow determined with the experiments of Sapone are too high, due to the spray root devices. The effect of these strips are discussed in Chapter 6, but still discussable. The amount of water landing on the ship determined with SHIPICE is 10 times lower than the experiments of Sapone. Therefore, the effect of a knuckled bow should be investigate more deeply.

The computation time of SHIPICE is largely depending on the amount of starting positions on the edge of the ship. The preferred amount of starting points used are depending on the bow shape angle as mentioned in Chapter 4. If the bow is very pointed more starting points are needed to have an accurate model. Therefore, the amount of steps used in SHIPICE should depend on the bow shape angle.

In the current model there is assumed that all the droplets are spherical shaped. For the smaller droplets this is a correct assumption, but not for the larger droplets. Non-spherical shapes will give a larger drag coefficient, which will influence the trajectory path of the droplets. A detailed study should be done about the effect of non-spherical droplets during the trajectory and the droplet cooling. On the other hand an increase in complexity will have a negative influence on the computation time.

Currently the geometry of the ship and the superstructure on top of the deck, are modelled very simplified. Having only straight flat panels and one superstructure on the deck. To get a better understanding of the influence of the different obstacles on a ship, there should be looked at the implementation of multiple superstructures on the deck of the ship. Also the area of the hit area intensity distribution should be smaller.
In the trajectory part of SHIPICE there are some uncertainties which will affect the model. For example the bow of the ship is not perfectly smooth, giving the spray an adjustment in their angle. Besides that the measured wind is not exactly blowing from one direction, but fluctuate around this direction. Therefore, there should be included a random term in the trajectory part.

In the trajectory part of SHIPICE there is only one location where the total mass of per droplet size is landing. To get a wider range of end-locations of the droplets a multivariate Gaussian distribution should be included. With as mean the one location that is determined in the current SHIPICE model.

In this thesis there was briefly looked at the effect of the spray impact. In Chapter 3 there is shown that in most of the cases there will occur splashing. How much effect this will have on the ice growth rate should be further investigated. The effect of this spray on the already accreted ice layer should be further investigated and implemented in the SHIPICE model.
Appendix A

The general conservation equations

A short recap about the basics of the conservation equations within the thermodynamics. The principles that can be applied to any problem are conservation of mass, momentum and energy. These equations are based on the difference in x-, y- and z-direction and time. Before these equations can be used a system boundary around the control volume need to be set up.

Conservation of Mass

The conservation of mass is generally quoted as: 'The mass that enters a system must, by conservation of mass, either leave the system or accumulate within the system.' Meaning that there cannot disappear or spontaneously emerge mass.

\[
\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho = 0
\]  

\( (A-1) \)

where:

\[ \mathbf{v} = u + v + w \]

\[ \nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \]

where \( \mathbf{v} \) is the local velocity with components in the x-, y- and z-direction, respectively. Eq. (A-1) is the mass per volume that differ in time depending on the in- and out flow of mass in x-, y- and z-direction.

Conservation of Momentum

Conservation of momentum is a fundamental law of physics which states that the momentum of a system is constant if there are no external forces acting on the system. It is embodied in Newton’s first law (the law of inertia).

\[
\rho \frac{D\mathbf{v}}{Dt} = -\nabla P + \mu \nabla^2 \mathbf{v} + \rho g
\]

\( (A-2) \)
where:

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + \nabla \mathbf{v}
\]

**Conservation of Energy**

The conservation of energy states that the total energy of an isolated system remains constant. Energy can neither be created or be destroyed, but it can be transformed from one form into another. A system without an external energy supply can never deliver an unlimited amount of energy to its surroundings. It is embodied in the first law of thermodynamics.

\[
\rho c \frac{D T}{Dt} = \nabla \cdot k \nabla T + \mu \Phi + \dot{Q}_v
\]

(A-3)

where \(\Phi\) is the dissipation function:

\[
\Phi = 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2
\]

This is the thermal energy equation for Newtonian fluid, like water and air.
Appendix B

Standard heat transfer parameters

Below the used equations to determine the standard used parameters for the heat transfer equations are determined.

Prandtl number:

\[ Pr = \frac{c_p \mu}{k} = \frac{\nu}{\alpha} \]  
(B-1)

Reynold’s number:

\[ Re = \frac{VL}{\nu} = \frac{VL\rho}{\mu} \]  
(B-2)

Schmidt number:

\[ Sc = \frac{\nu}{D_w} \]  
(B-3)

Diffusivity of water:

\[ D_w = -2.775 \cdot 10^{-6} + 4.479 \cdot 10^{-8}T_a + 1.656 \cdot 10^{-10}T_a^2 \]  
(B-4)

Saturation specific humidity

\[ q = 0.0622 \frac{e_s(T)}{P_a - 0.378e_s(T)} \]  
(B-5)

Saturation vapour pressure:

\[ e_s(T) = 611.2 \exp \frac{17.67T}{T + 243.5} \]  
(B-6)

where \( T \) is the temperature in Celsius.

Latent heat of vaporization:

\[ l_v = 2500.8 - 2.36T + 0.0016T^2 - 0.0006T^3 \]  
(B-7)

Recovery factor:

\[ \beta = 1 - \left( \frac{U}{U_0} \right)^2 \left( 1 - Pr_a^{1/3} \right) \]  
(B-8)


W. Bruce. Automated image analysis for marine icing events.


C.M. Hoes  
Master of Science Thesis


