Proceedings of the 26th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2021, Moscow, Russia

Brash ice formation on a laboratory scale

Vasiola Zhaka [1], Robert Bridges[2], Kaj Riska[3], Andrzej Cwirzen[1]
[1] Luleå University of technology, Luleå, Sweden
[2] Total. S.A, Paris, France
[3] Formerly Total. S.A, Paris, France, retired

ABSTRACT

Frequent navigation in ice-infested waters causes brash ice formation and accelerated ice growth. Large ice accumulation in ports and vessel tracks can hamper maritime activities. Therefore, the forecast of brash ice occurrence requires accurate prediction models based on frequent and comprehensive observations and measurements. However, field and large-scale laboratory testing for thorough brash ice investigation require significant resources. The current work outlines experiments on the formation of a freshwater brash ice channel in a tank. The tank was exposed to outside weather conditions during winter meteorological conditions in Luleå, Sweden, where the air temperature went down to -25^{O}C. The channel's geometry and ice thickness evaluation were systematically measured. The results gave insights into the laboratory-scale brash ice formation. Moreover, the influence of snowfall on brash ice solidification in the early winter is observed. The observed brash ice formation and especially thickness is reported and compared with predicted values. The work concludes by discussing the advantages, challenges, and limitations of this laboratory-scale brash ice formation method derived from the current tests.

KEYWORDS: Brash ice; ice accumulation; ice thickness; laboratory-scale test.

1. INTRODUCTION

An important challenge in the daily port operations is the accelerated growth of brash ice thickness caused by the frequent vessel passages in ice-infested channels, see Figure 1. The frequency of the navigation and the amount of the cumulative freezing degree days were found to be the main parameters that control the accelerated ice production in ship channels, (Sandkvist, 1986). However, after each vessel passage, a fraction of the ice volume produced is moved sideways and pile under the adjacent level ice to form the side ridges. The lateral ridge structure confines the brash ice and permits the brash ice pieces to accumulate and increase the channel thickness (Greisman, 1981). Among other factors, vessel geometry influences the ice movement and distribution of brash ice due to ship bow pushing ice sideways and propeller current scattering ice (Kitazawa and Ettema, 1985, Ettema, Schaefer, and Huang, 1998). Full-scale measurements in a brash ice channel in the Bay of Bothnia showed an ice amount that corresponds to an equivalent brash ice thickness of 2.5 m after 33 passages and 1700 cumulative freezing degree days (CFDD) while the maximum level thickness measured was 0.82 m (Sandkvist, 1980). Moreover, measured values in the Arctic have indicated brash ice thicknesses of 3 to 4 m (Riska et al., 2019), where CFDD may reach 4200^{o}C·days in severe winters.

Vessel navigation, port layout design, and operational strategies depend on the reliability of the brash ice forecast models. The validity of the brash ice models relies on the physical and thermal parameters' accuracy, and increasing accuracy requires systematic observations and measurements. However, continuous measurements in full-scale channels are not always feasible, considering the costs and assets required. Therefore, the current work presents results obtained from a laboratory-scale channel generated in a water tank exposed to the outside freezing weather conditions. The current investigation aims to characterize the experimental conditions that influenced the channel formation and development in tests conducted during early winter. The level ice thicknesses measured over the first test are validated with both Stefan (1889) and Ashton (1989) ice growth equations while the brash ice equivalent thickness is fitted with the brash ice equation proposed by Sandkvist (1981).

Figure 1. Brash ice channel in Luleå coast, Sweden, 2021. The photograph is recorded onboard of port icebreaker tug *Viscaria*, Luleå Hamn.

2. Test arrangements

Two experiments were conducted in early winter at the Luleå University of Technology, Luleå, Sweden, to investigate the brash ice formation and development in natural meteorological conditions. The experiments comprised of the formation of a brash ice channel in a steel tank during two different periods, mid-December 2020 and mid-January 2021. The channel was formed from repeated ice-breaking followed by the growth of an initial intact ice layer.

2.1 Tank set up

A steel tank with inside dimensions of 0.65 m x 1.2 m x 1.8 m (width; depth; height) was insulated with Styrofoam at the bottom and the side walls. A small window on one side of the tank made the underwater observations possible. The tank was filled to one-meter depth with fresh water. The breaking procedure was carried out manually. During the first test, a triangular-shaped metal plate was used to break the ice, followed by a vertical metal plate, with widths respectively 14 and 7 cm. This formed a so-called brash ice channel along the length of the tank. During the second test, a small hammer was used to provide the initial break followed by the vertical plate. The brash ice channel formed in the steel tank is illustrated in Figure 2.

2.3 Measurements

The air and water temperature distribution were monitored continuously with four thermocouples in both tests. The thermocouple that measured the air temperature was mounted 30 cm above the water level. Three thermocouples were placed in different depths; on the water surface, 3.5 cm and 10 cm below the surface. The tips of the thermocouples were located at the center of the long side of the tank and approximately 10 cm from the side.

Thickness measurements were conducted before the breaking events along the cross-section of the channel. The snow and ice thickness were measured every 5 cm along the cross-section of the channel. The ice thickness was measured by drilling mechanically along the cross-section and measuring the ice bottom with a ruler. In addition, the channel width evolution after each breaking event was observed by photograph recording along the length of the tank, and an average width was estimated from the images.

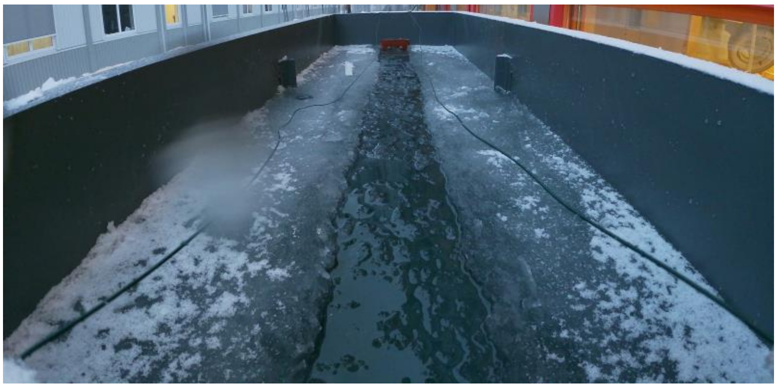


Figure 2. Example of the brash ice channel formed from exposer to the outside meteorological condition.

3. Test program and execution

A brief discussion is given on the weather conditions, data gathered and analyzed during both tests. The air temperature was recorded and the CFDD was determined. The cumulative freezing degree days θ is based on Stefan's (1989) approach:

$$\theta = \int_0^t (T_f - T_a)dt, \tag{1}$$

where T_f and T_a are the freshwater freezing and air temperature. Freezing is considered here to initiate at 0°C. In addition, the change in channel thickness, width, and the influence of snowfall observed during the experiments are discussed and illustrated.

3.1 Test 01-December

The first test lasted approximately 8 days. For the first 4.5 days, the air temperature oscillated between -2.5 and 2.5^{O}C, and the initial water temperature immediately after filling the tank varied with depth from 8 to 9^{O}C. The snowfall that occurred during this time contributed to the formation of a snow-ice layer, which gradually melted and after 4.5 days a snow-ice skim covered partly the surface of the tank. Thereafter, the air temperature decreased below 0^{O}C and induced ice formation. During the second period of the first experiment, which consisted of approximately 3.5 days, the temperature varied from -5.5 to 0^{O}C. An overview of the temperature during the first and the second period of the first experiment is illustrated in Figure 3.

The first breaking event (BE) occurred once the ice reached a thickness of 0.5 cm after the start of the second period. In total the channel was broken 13 times in 3.5 days and every breaking event was followed by 4 passages along the channel with the vertical plate. The cross-section thicknesses were measured before the breaking events. An example of the thickness evolution with time along the width and the cross-section of the channel before the final BE is given in Figure 4. The cross-section indicates the level ice on the edge of the tank and the side ridges at the edge of the channel and a progressive increase in thickness after each breaking event. However, it should be noted that the thickness measured in the channel represents the consolidated layer between two consecutive passages and not the actual slush accumulation underneath. In addition, as shown in Figure 4a, after the 12th BE the layer of snow and ice above the freeboard is higher than the buoyant capacity of the floating ice, a phenomenon that causes the increase of water level above the ice surface (Lepparanta, 1983). However, in our tests, the ice was frozen and stabilized to the tank's edge and the submergence of the ice below the waterline did not occur. Apart from this phenomenon, the tank walls were not observed to influence the ice growth since there was a short testing time and sufficient insulation.

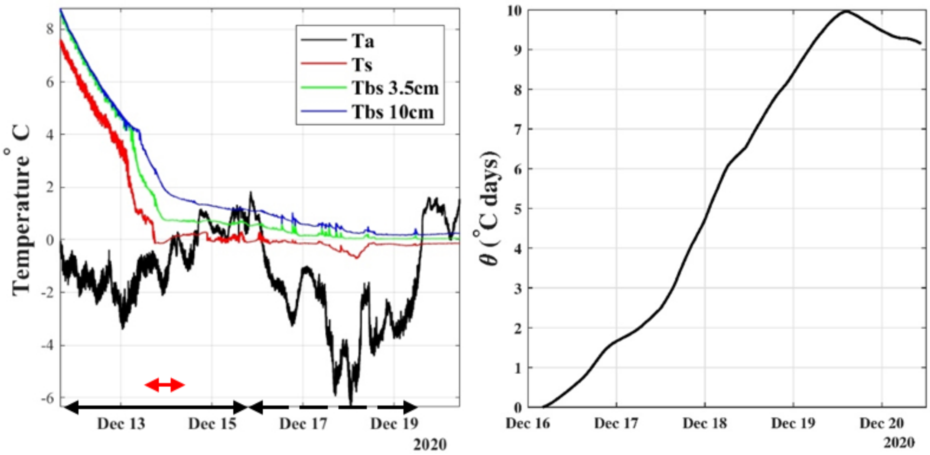


Figure 3. a) The air temperature, surface, and at 3,5 and 10 cm below the surface, during the first tank experiment, are noted as Ta, Ts, Tbs 3.5, and Tbs 10 respectively. The black arrow represents the first 4.5 days after the water tank was filled with water, the red arrow shows the time that a 4 cm snowfall occurred and contributed to an initial ice-snow layer of 1cm. The black dashed arrow represents the second period of ice growth and brash ice channel formation during which the channel was broken. b) the CFDD for the second period of the experiment. The decrease in the CFDD after 3.5 days shows the increase in air temperature experienced at the end of the test.

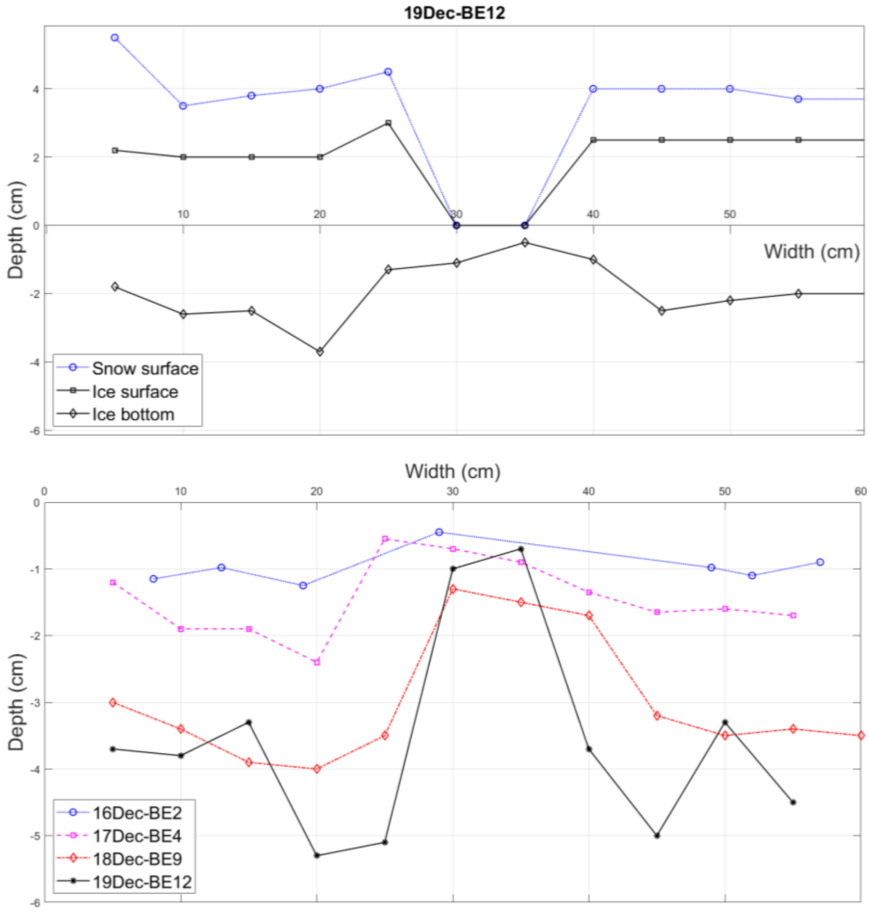


Figure 4. a) Example of channel cross-section profile measurements from the waterline after the 12th breaking event of the first test. b) The development of the refrozen brash ice cross-section profile with time. Note, the x and y-axis are on different scales.

3.2 Test 02-January

The second test lasted approximately 3.5 days. The air temperature varied from -25 to -1^{O}C. The initial water temperature varied with the depth between 6.5 to 8^{O}C. Snowfall during the first day induced heat loss and initiated the ice formation a day after the tank was filled with water.

The ice was initially broken to form the channel when the level ice thickness reached 1.05 cm. The channel was broken 17 times within 3.5 days. An overview of the temperature evaluation and the evolution of CFDD is illustrated in Figure 5.

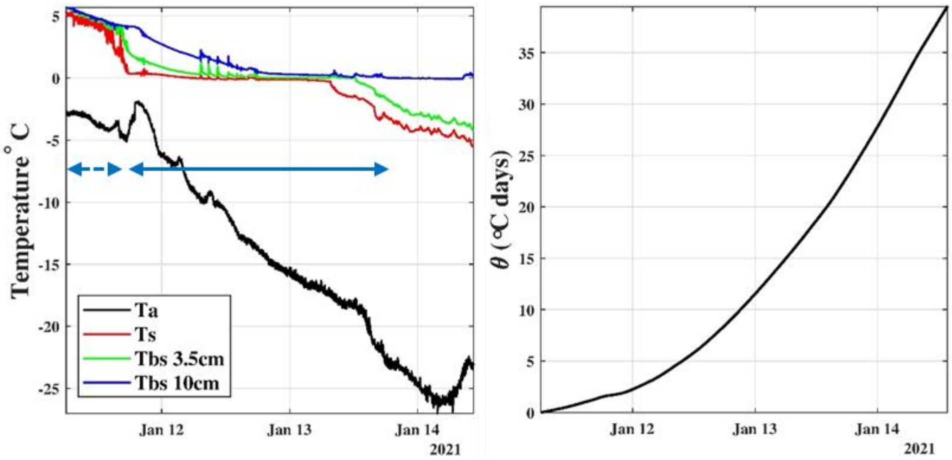


Figure 5. a) The air temperature, surface, and at 3,5 and 10 cm below the surface, during the first tank experiment, are noted as Ta, Ts, Tbs 3.5, and Tbs 10 respectively. The dashed blue arrow represents the period of water heat loss before the ice formation started. The blue arrow shows the duration from the initial ice formation and during the breaking period. b) The evolution of CFFD over the experiment duration.

4. Observations of the channel's development

A significant difference was observed with channel formation between tests. The initial breaking for both tank tests generated thin ice floes. However, in the first test, the ice floes were about 3 to 10 cm wide and were pushed under the level ice resulting in an open water channel as illustrated in Figure 7 (photos 1,4,5). In the second test after the first breaking, the floes were as big as the channel width and mostly remained in the channel. The ice blocks in a full-scale brash channel are found to be up to 2 m (Mellor, 1980), which is a smaller value in comparison with the beam of vessels or width of channels. The warm air temperatures and the occurrence of snowfall at the start of the first test probably reduced the strength of ice. Therefore the difference in the floe sizes between the tests can be considered the result of the 0.55 cm change in the initial level ice thickness and the breaking length/ice thickness ratio, which is found to be lower for the weak ice compared to strong ice e.g. (Li, Yue, and Shkhinek, 2003).

Furthermore, in contrast to full-scale observations, the average channel width was observed to reduce from the initial width; 6 and 14 cm in the first and second test respectively, see Figure 6. During both tests, the cause for the reduction in width may be attributed to the manual breaking procedure which required greater effort to be exerted owing to the continuous increase in brash ice thickness. In the future, further attention will be given to developing a more reliable breaking mechanism and process. However, the width of the channel in both experiments reached a constant value, which was equal to the beam of the breaking tool. For simplicity, the width of the channel is taken as a constant parameter for the brash ice thickness models discussed in the following section.

In addition, the snowfall occurrence after the 9th BE until 13th BE in the first test caused slush formation in the channel, and also between the level ice and snow layer. The slush formed in the channel prohibited the lateral movement of ice pieces, thus reducing the open water surface in the channel, as in Figure 7 (photos 2,3,6). During the second test, continuous snowfall occurred after the second BE, and the side movement of the ice floes was lower compared to the first test, see Figure 8.

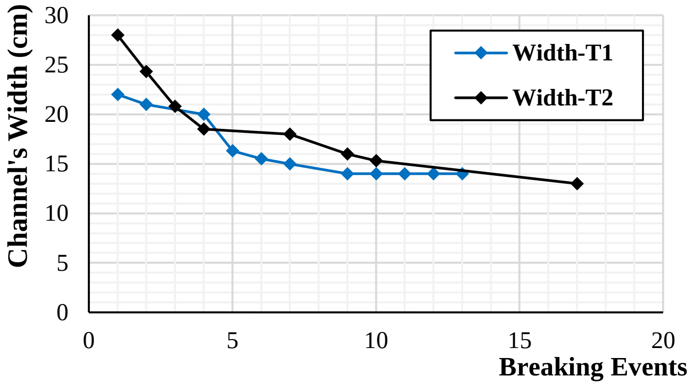


Figure 6. Channel's width development with the breaking events in Test 01 (T1) and Test 02 (T2).

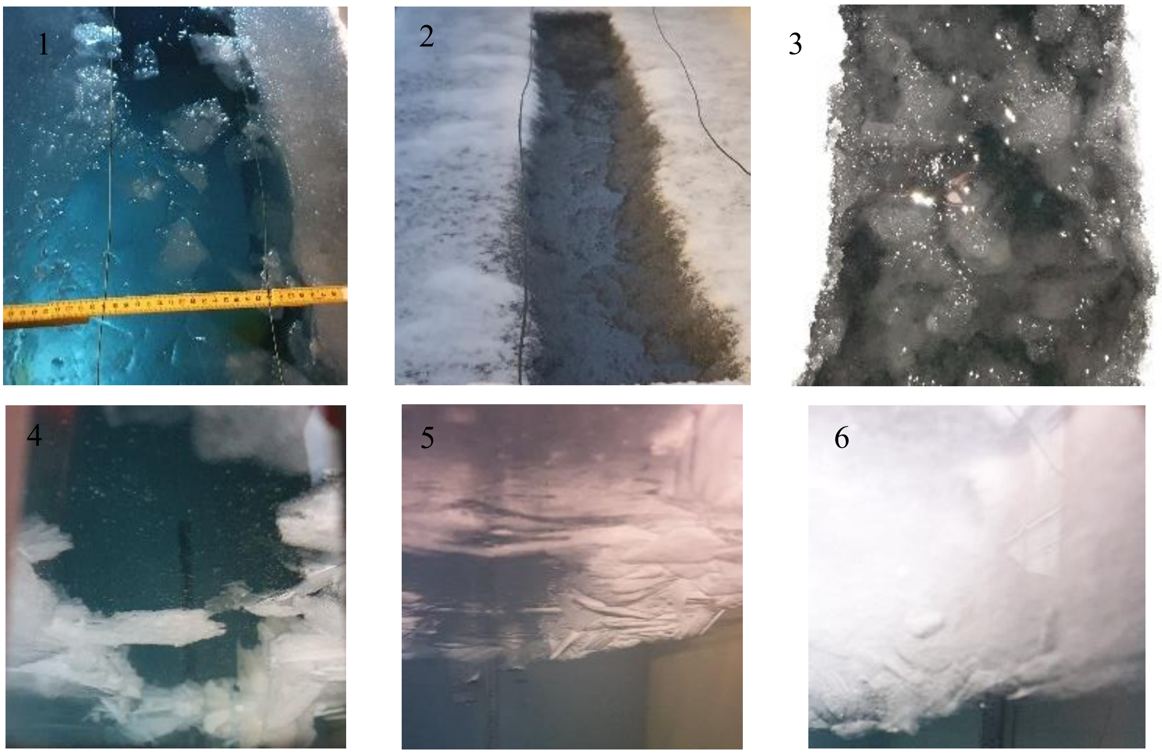
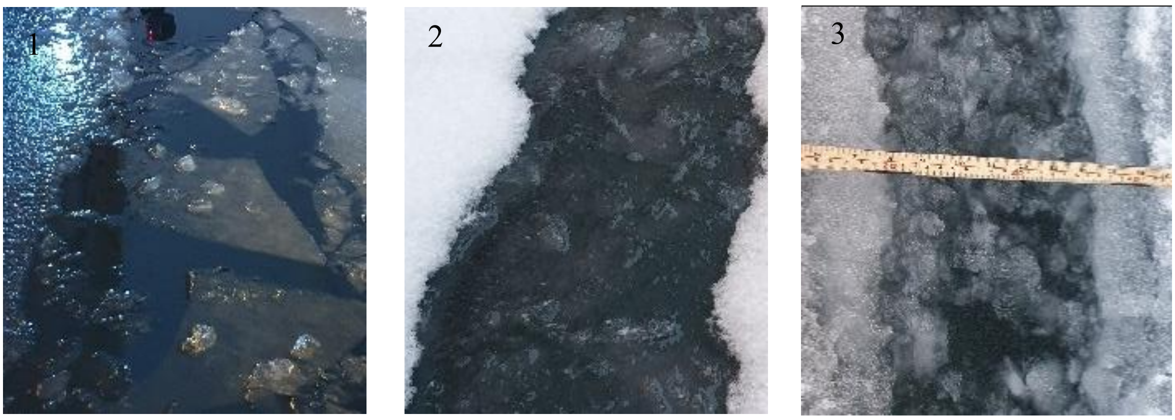


Figure 7. The sequence of brash ice formation during test 1. The figures illustrate the top view and underwater view. Photos 1 to 3 show the top view: after 2nd; before 10th and after 12th BE, and 4 to 6 shows the underwater view: after 1st; 3rd and 13th BE.



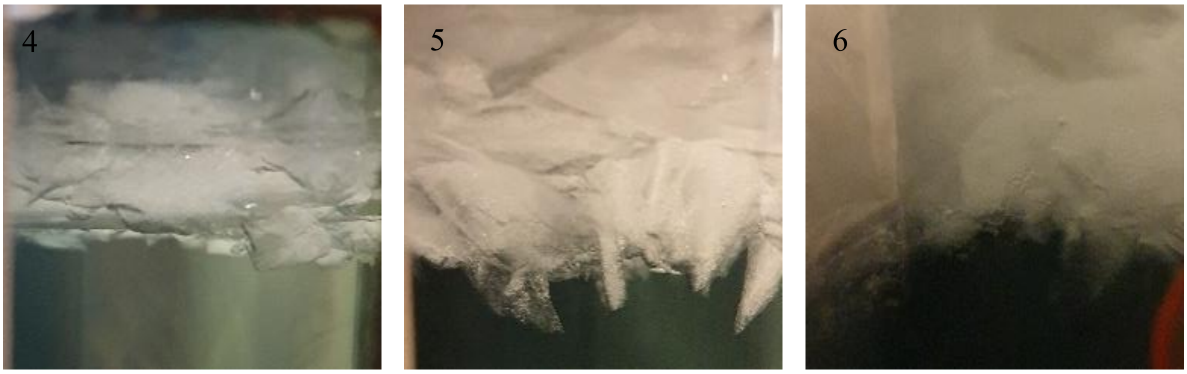


Figure 8. The sequence of channel brash ice formation during the second test. The figures illustrate the top view and underwater view. Photos 1 to 3 show the top view: after 1st; 4th and 10th BE, and 4 to 6 show the underwater view: after 1st; 5th and 9th BE.

5. Discussion

The measured level ice thicknesses and equivalent brash ice thicknesses of the channel are compared with those from predicted models.

5.1 Level ice growth

In a full-scale brash ice channel, the level ice thickness is typically determined from the adjacent ice that is not affected by the side movement during vessel passages. In the current case, the level ice at the sides may not be realistic owing to the possible displacement of the ice reaching the sides of the tank. To illustrate this, the ice thicknesses measured at the edge of the tank, h_{ed}, during the first test are compared with values estimated by Stefan's equation for static ice growth (Stefan, 1889), equation 2, derived by Ashton (1989) based on Stefan's approach including air-ice coupling, equation 3:

$$h_S = \alpha\sqrt{\theta} \tag{2}$$

$$h_A = \sqrt{\left(\frac{k_i}{h_a}\right)^2 + \frac{2k_i}{\rho_i L_i}\theta} - \frac{k_i}{h_a} \tag{3}$$

Where α is the growth rate coefficient and θ is the cumulative freezing air temperatures given in equation 1. k_i= 2W/m/°C is the thermal conductivity coefficient of ice, ρ_i = 910 kg/m3 is the ice density, L_i=$335\cdot10^3$ J/kg or 3.88 Wdays/kg is the latent heat of ice formation and h_a= 22 W/m^2/ °C is the convective heat transfer coefficient in the ice –air interface.

The measured values appeared to correlate reasonably well with α = 0.89 cm/(°C days)$^{0.5}$. However, the values measured on the second and third day do not follow Stefan's model, see Figure 9. In addition, the theoretical α yielded from Stefans equation is given by:

$$\alpha = \sqrt{\frac{2k_i}{\rho_i L_i}} = 3.4 \ \text{cm/(°C days)}^{0.5},$$

The difference between the theoretical and empirical rate of freezing could be attributed to the snowfall synergetic effect, including the growth rate decrease due to snow (Nakawo & Sinha,

1981) and the slush formation followed by the snow-ice formation between ice and snow layer (Lepparanta, 1983). As noted above the ice layer was isostatically imbalanced and the freeboard remained below the ice surface. Therefore the surface growth was not affected by the water level changes. In the current experiments, the snow-ice formed on the adjacent level ice from the hydrodynamic effect during each BE which resulted in water splashing onto the ice surface. The significance of snow on the ice growth will be further investigated.

Furthermore, level ice thickness predicted using Ashton's (1989) values fit the measured thickness for a convective heat coefficient equal to 22 W/m^2/^{o}C. However, in this case, there is a difference between the model and measured values. Due to these differences, we consider that the ice side movement influences the refrozen ice layer measured in the tank's edges.

5.2 Equivalent brash ice thickness

The brash ice accumulation on the first test was estimated based on the assumption of equivalent brash ice thickness (Sandkvist, 1980). In this case, it is assumed that the ice pieces accumulate in the brash ice channel with a width equal to the vessel's beam and the lateral displacement of the ice pieces under the level ice is neglected. Based on these principles, the measured values of the refrozen brash ice across the tank are converted to the equivalent thickness H_{eq} using the following expression:

$$H_{eq} = \Sigma\left[w_i * (H_{rbi} - h_{ed)} + (w_i * H_{bi})\right]/w_{ch} \quad (4)$$

Where w_i represents the distance between two consecutive measurements along the cross-section taken every 5cm and w_{ch} is the channel width considered equal to the width of the breaking equipment, 14 cm. H_{rbi} is the thickness of the ridged brash ice on the sides of the channel and H_{bi} is the brash ice thickness measured in the channel.

A simple freezing degree day model developed by (Sandkvist, 1981) is used to compare values of the measured equivalent thickness with the predicted values. The model estimates the equivalent brash ice thickness accumulated in a channel after each vessel passage i. Where the width of the channel is equaled to the vessel's beam. The predicted equivalent brash ice thickness H_{Seq} at time t is given as follows:

$$H_{Seq} = \sum_{i=1}^{i} \alpha\, (\Delta\theta_i)^{0.5} \quad (5)$$

The cumulative degree-days between two vessel passage are equal to $\Delta\theta_i=\theta_i-\theta_{i-1}$, where i is the number of vessel passages. The original model proposed includes the level ice thickness before the first breaking event. However, since this is uncertain we use the air temperature to determine the level ice thickness before the breaking event. Also, the model does not include the brash ice porosity and assumes that the ice produced after each breaking event is accumulated and fully consolidated in the channel's width equal to the vessel's beam. Figure 10 shows the measured brash ice thickness in comparison to the estimated brash ice thickness from Sankvist's model. The difference between the measured and predicted values may be attributed in part to the measured thickness was just that of the refrozen ice layer, and neglected the slush underneath. One of the main factors for the slush content observed in these tests was the snowfall occurrence. This slush formation due to snowfall and its effect on the side movement and freezing rate requires further investigation.

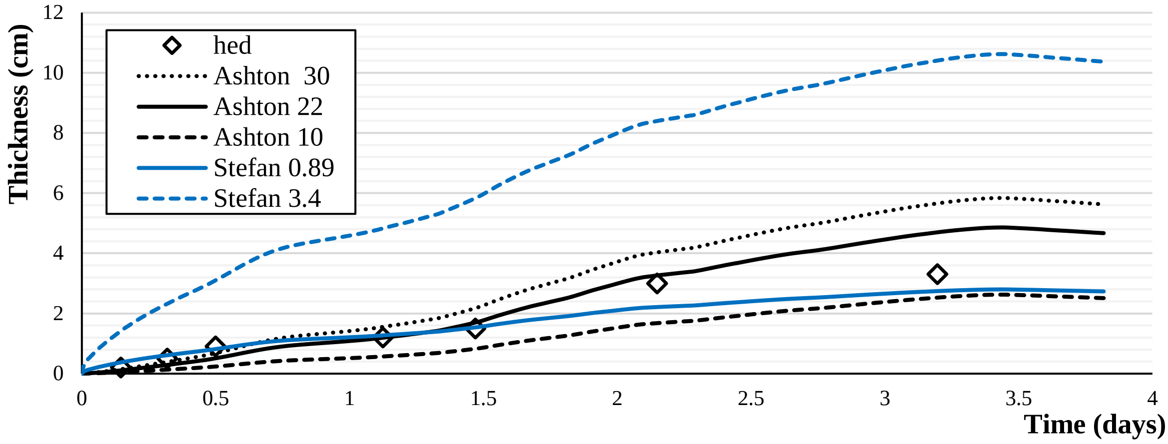


Figure 9. Thickness development of the ice measured at the edge of the tank, and level ice thickness estimated with Ashton (1989) for three different convective heat transfer coefficients equal to 10, 22, and 30 W/m2/°C and with Stefan (1889) for the theoretical and empirical α equal to 3.4 and 0.89 cm/(°C days)$^{0.5}$ respectively.

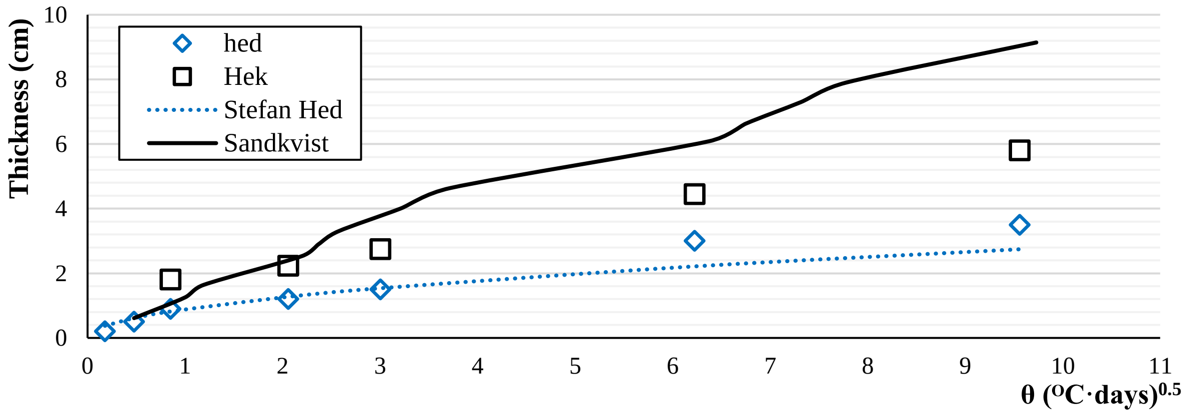


Figure 10. The measured level ice thickness (h_{ed}) at the channel edge, the equivalent brash ice thickness (Heq) from the measured values of the refrozen ice across the channel width. The fit of Stefan's equation for h_{ed} and the Sandkvist model results.

CONCLUSIONS

Two laboratory tests were conducted at Luleå University of Technology during December 2020 and January 2021 to study the brash ice channel formation and development on a laboratory scale. The experimental setup was a preliminary test aiming to provide insights into the overall method reliability. The experiments were conducted in a tank exposed to the winter weather conditions in Luleå, Sweden. The air temperature variation throughout the experiment, the geometry of the channel, and the thickness development were measured.

The experiments conducted on a small scale demonstrated the feasibility of indicating possible parameters that affect the brash ice formation and development. The tests highlighted the effect of the breaking procedure and the initial ice thickness have in the piece size distribution and the width of the channel. In addition, the effect of snowfall on the brash and level ice thickness may be significantly important and will be the focus of future laboratory tests and research.

The laboratory-scale brash ice channel formation is a promising method for indicating and systematically measuring parameters that can be introduced and improve the accuracy of the brash ice forecast models. The tests will continue outdoors in the winter and in the cold room during summer.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from Total.S.A and Kolarctic ICEOP, and also the help and assistance received from the technical operators of the Luleå University of Technology.

REFERENCES

Ashton, G. D. 1989. "Thin Ice Growth." *Water Resources Research* 25(3):564–66.

Ettema, R., J. A. Schaefer, and H. P. Huang. 1998. "Ice-Tank Data on Brash-Ice Loads against Barges." *Journal of Cold Regions Engineering* 12(3):153–61.

Greisman, P. 1981. "Brash Ice Behavior." *U.S. Coast Guard Research and Development Center*, Report No. SCG-D430-81.

Kitazawa, T. and R. Ettema. 1985. "Resistance to Ship-Hull Motion through Brash Ice." *Cold Regions Science and Technology* 10(3):219–34.

Lepparanta, M. 1983. "A Growth Model for Black Ice, Snow Ice and Snow Thickness in Subarctic Basins." *Nordic Hydrology* 14(2):59–70.

Li, F., Q. J. Yue, and K. N. Shkhinek. 2003. "A Qualitative Analysis of Breaking Length of Sheet Ice Against." *Proceedings of the POAC Symposium on Ice. Trondheim Norway: POAC International Committee* (1998).

Mellor, M. 1980. "Ship Resistance in Thick Brash Ice." *Topics in Catalysis* 3(4):305–21.

Nakawo, M. and N. K. Sinha. 1981. "Growth Rate and Salinity Profile of First-Year Sea Ice in the High Arctic." *Journal of Glaciology* 27(I):315–30.

Riska, K., R. Bridges, S. Shumovskiy, C. Thomas, E. Coche, V. Bonath, A. Tobie, K. Chomatas, and R. Caloba Duarte de Oliveira. 2019. "Brash Ice Growth Model – Development and Validation." *Cold Regions Science and Technology* 157:30–41.

Sandkvist, J. 1981. "Conditions in Brash Ice Covered Channels With Repeated Passages." *In POAC 81 : The Sixth International Conference on Port and Ocean Engineering under Arctic Conditions, Québec, Canada July 27-31, 1981, Proceedings.* 244–252.

Sandkvist, J. 1980. "Observed Growth of Brash Ice in Ships' Tracks." *Research Report; Series A No. 42* (Div. of water resources engineering, University of Luleå).

Sandkvist, J. 1986. "Brash Ice Behaviour in Frequent Ship Channels." *(Licentiate Dissertation)* (139).

Stefan, J. 1889. "Über die Theorie der Eisbildung, insbesondere über Eisbildung im Polarmeere." *Ann. Physik, 3rd Ser* 42:269–86.