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

Scale-model ridges and interaction with narrow structures, Part 2: thermodynamics of ethanol ice

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ABSTRACT

This study characterizes the refreezing process of the deformed dopant ice. Both basin and laboratory experiments were conducted to study the influence of ethanol dopant on level ice and ice ridge consolidation rate and their mechanical properties. Experiments covered a ridge block thickness of 4 cm, ethanol concentration of 0.3% and freezing time of 7-12 hours at the temperature of -12 °C, experiments measuring flexural and compressive strength, and ice-structure interaction with cylindrical and conical structures. Study presents the influence of freezing and warming time on the mechanical parameters of model ice as well as differences between growth, temperature profile, and structure of ice from water-ethanol mixture and from pure water. The freezing process results for ethanol and fresh level and deformed ice were compared with developed thermodynamic models for fresh and dopant ice.

KEY WORDS: Ice ridge; Dopant ice; Thermodynamics; Model test; Ice growth.

INTRODUCTION

Motivation

Ice ridges often represent the design loads for coastal and offshore structures (Ervik et al., 2019). Ridge loads are usually estimated using basin tests, analytical and numerical models. For a full-scale measurement, a structure should be equipped with load measuring devices, while ridge morphological parameters should be measured before the interaction, which is practically impossible. Basin tests are almost the only physical way to validate a model. But basin tests require a choice of scaling method for both mechanics and thermodynamics, which are often interconnected, because ice mechanical parameters are temperature dependent.

Basin tests are providing a unique chance to study interaction of ice ridges and structures. Geometrical scaling of such interaction under generally accepted scaling rules requires scaling of ice mechanical parameters and microstructure which is only possible using dopants and spraying. While mechanical parameters of a model level ice produced by spraying is well studied for conditions of a specific ice basin, it is little known about mechanical parameters of refrozen ice or as called consolidated layer of ice ridges. This layer cannot be produced by spraying so its microstructure is different from the model ice.

This study attempts to investigate process of consolidation of ethanol ice ridges and to find similarities and differences with freshwater ice ridges. It is also aiming to provide an accurate thermal and morphological data for further analysis of ice-structure interaction during test in Aalto ice tank. For that purpose, we performed a series of laboratory experiments aiming:

- To compare growth of LI and CL from pure water and ethanol solution.
- To find ice thicknesses of LI and CL for basin test thermal conditions.
- To find connection between ice thickness and its temperature profile.

Previous studies

There are several different types of model ice. In some basins including Hamburg Ship Model Basin, Krylov State Research Centre, and Aker Arctic, natrium-chloride water solution is used together with bottom ice growth. Ethylene-glycol-aliphatic-detergent-sugar (AG/AD/S) dopant is used at NRC Ottawa Ice tank (Timco, 1986), ethanol dopant is used at the Aalto university ice basin (von Bock und Polach et al., 2013), where ice is growing from the top.

There is a limited amount of studies dealing with the consolidation of basin scale ridges. Timco and Goodrich (1988) presented results of AG/AD/S model ice ridge consolidation with the range of thickness of 10-30 cm and compared thickness values from direct measurements and from temperature profiles analysis. ITTC (1999) recommend scaling the consolidation time as the square of the geometric scaling factor from the Stefan equation of ice growth.

There is also a small number of studies presenting results of level ice solidification from different water-based solutions. It can be explained by only 4% difference between sea ice growth predictions with different salinity profiles (Griewank and Notz, 2013). Meanwhile, saline level ice cooled from below due to the absence of the ice desalinization process is growing faster than fresh ice in laboratory scales (Notz, 2005).

METHODS

Methods of laboratory experiments

Laboratory experiments in consolidation of ice ridges formed from freshwater and ethanol solution were performed at the cold laboratory of NTNU at the air temperature of -17 °C. Ice was grown in two identical acrylic cylindrical water tanks with a diameter of 30 cm and side insulation. Ice ridges were grown using additional insulation forming water voids of 18x10 cm horizontal cross-section. Thickness of vertical blocks, forming ridges, was around 4 cm, like in the performed basin experiments, the ridge macroporosity was around 33%. In one of the water tanks ethanol concentration was 0.3%, while other one was filled with freshwater. 9 level ice and 16 ridge experiments were performed to study freezing process of both liquids under the same external thermal conditions.

Both ice ridges were equipped with two thermistor strings: one in the middle of the void and one in the middle of the block. For the half of the ridge experiments ice blocks had initial temperature of -15 °C, other half of the ridges were made of worm blocks at -1 °C. After the end of each experiment ice was taken away from the water tank, thickness of consolidated layer and surrounding level ice was measured.

Growth of ice from ethanol solution is not a well-studied process according to authors knowledge. It has some similarities with saline ice growth, it also consists of liquid and solid parts whose proportions are temperature and concentration dependent. But there are also significant differences, especially at the ice bottom surface boundary conditions. Saline ice is expelling salt, so its bulk salinity is significantly lower than salinity of the water from which it was formed. This process is mainly driven by the difference in densities between more dense and saline brine and less dense underlying water. Mixture of water and ethanol is lighter than pure water, so there is no reason to expect significant differences in ethanol concentration in solid and liquid. This might lead to very high liquid fraction at the bottom of ethanol ice and faster ice growth. To model growth of ice from ethanol solution its liquidus temperature should be set as a thermal boundary condition at the interface of solid and liquid parts.

Methods of basin tests

The model tests were performed in the ice tank of Aalto University. It is a 40 m by 40 m basin with 2.8 m water depth equipped with a cooling system and a carriage. The model ice for ridge creation was granular fine-grained ice produced by spraying the basin water from the moving carriage at -10°C. After reaching a design ice thickness of 40 mm, the air temperature is lowered to -12°C. A target model ice strength is obtained by warming ice. A Froude scaling was used with a geometrical and flexural strength scale factor as 15 (Table 1). A total of three level ice sheets were produced, one ridge per ice sheet was built.

Table 1. Main parameters of ice tank experiments for basin and full scale

Parameter	Basin scale	Full scale
Level ice thickness h_i	4 cm	0.6 m
Keel depth h_k	40 cm	6 m
Sail height h_s	8 cm	1.2 m
Target flexural strength σ_f	50 kPa	0.75 MPa
Cylinder diameter d	50 cm	7.5 m

Ice was produced from pure water with 0.3% fraction of ethanol. Ridge block thickness was 4 cm for all 3 ice floes. Structure moving speed was 4 cm/s. Cylinder diameter was 50 cm. Ethanol-water liquidus temperature is -0.12°C.

Air temperature development for different stages of experiment together with measured values of level ice flexural strength is presented in Shestov et al. (2020). The first stage is spraying, when model ice is produced and cooled down to reach a certain mechanical property. After the measurement of the flexural strength, level ice can be tempered at freezing temperature or warmed to reach a preferable value of strength. When the strength is close to the needed value, a part of level ice can be broken with carriage, and a ridge can be produced from that ice by pushing broken ice using pushing plates and anchoring surrounding level ice. After that ice-structure interaction test with unconsolidated ice ridge can be performed. It follows by ridge consolidation at -12°C and ridge warming. When level ice flexural strength is measured again, ice-structure interaction test can be performed again with consolidated ridge.

The maximum and average keel depth of 40 cm and 35 cm were measured for the floe 3 by vertical profiling. Average measured sail height was 8 cm. Ridge 3 was produces from 40 m by 24 m ice floe with 4 cm thickness. Based on the volume of sail, keel, and initial ice for the ridge production we estimated ridge initial macroporosity of 0.31.

To get temperature measurements two thermistors were installed in the old and new level ice and two thermistor strings were installed in the ridge. The length of each thermistor string is 40 cm, the minimum sensor spacing is 1.3 cm, time step was set to 10 minutes. We used strings from GeoPrecision GmbH with TNode EX sensors with 0.1°C accuracy in the temperature range from -20°C to +25°C. Heat flux above ice top surface was manually measured using heat flux plate Hukseflux HFP01-05 for the ice floe 3.

Analysis of temperature data from the basin tests involves two main objectives: estimation of thickness development and vertical heat fluxes. A series of laboratory experiments were performed to develop and confirm algorithms for estimations of these parameters in the controlled environment.

Both laboratory and basin test results will be compared with results of our analytical and numerical models of level ice and ridge solidification. Analytical values of freshwater ice thickness were estimated as:

$$h_c = \left(\frac{2k_i}{\rho_i L_i \eta}\left(T_f - T_a\right)t + \left(\frac{k_i}{H_{ia}}\right)^2\right)^{0.5} - \frac{k_i}{H_{ia}}, \quad (1)$$

where k_i is the ice thermal conductivity, ρ_i is the ice density, L_i is the ice latent heat, η is the macroporosity (1 for level ice), T_f is the liquid freezing temperature, T_a is the air ambient temperature, t is the time.

For basin tests the value of heat transfer coefficient H_{ia} was found from the manually measured convective flux q_a and ice thickness h_i assuming equal convective and conductive fluxes as:

$$H_{ia} = \left(\frac{T_f - T_a}{q_a} - \frac{h_i}{k_i}\right)^{-1} \quad (2)$$

Freshwater model is described in detail in Salganik et al., (2020), model for saline ice is described in Salganik et al. (2021).

RESULTS

Results of laboratory experiments

During our tank experiments we had a ridge consolidation with freezing indexes of 50, 62 and 101 FDH at the air ambient temperature of -12°C (Shestov et al., 2020). Heat flux above level ice measured during spraying is giving heat transfer coefficient value of approximately 10 W/m^{2}K. For these values according to our analytical solution we can expect freshwater level ice thickness of 6 and 12 mm for 50 and 100 FDH, respectively. For the ridge porosity of 0.31 (like in our basin and laboratory tests) estimated thickness of the freshwater consolidated layer is 17 and 34 mm for 50 and 100 FDH.

Freshwater level ice growth is a well-studied process. Thin ice growth is governed by the value of the heat transfer coefficient H_{ia}, which can be found experimentally for laboratory conditions using Eq. (1). Additional laboratory experiments were performed to check the relation between fresh and ethanol ice growth for both level ice and ridges. It was found that level ice grown from the ethanol solution is growing 15% faster and consists of two parts: strong consolidated upper part and weak dendritic lower part. Thickness of the bottom dendritic layer had thickness of approximately half of the total ice thickness (Figure 3a). Measured thickness was 6 mm and 9 mm (50 FDH), 12 mm and 16 mm (100 FDH) correspondingly for freshwater and ethanol level ice. For the same conditions consolidated layer was 23 mm and 27 mm (51 FDH), 50 mm and 48 mm (100 FDH) for freshwater and ethanol solution. Average ridge macroporosity for these laboratory experiments was 0.32. Opposite to level ice, ridges from ethanol solution did not have weak dendritic layer and were growing as fast as fresh ice (Figure 3b).

Ice growth comparison

To analyse and compare conditions in the NTNU laboratory and Aalto ice basin, it is necessary to estimate the average in time heat transfer coefficient H_{ia}. For the NTNU laboratory its value was estimated from the level ice growth observation to be 13 W/m^{2}K (Figure 1a). For level ice growth in vicinity of the model ridge, the heat transfer was around 15 W/m^{2}K, slightly higher due to surface roughness. The heat transfer coefficient for the Aalto ice basin, estimated from the measured heat flux and ice thickness, was around 10 W/m^{2}K.

Table 2. Laboratory and basin experimental values of ice thickness compared with analytical and numerical thickness estimation using heat transfer coefficient H_{ia}=10 W/m^{2}K.

Floe	Type	FDH	Solution	h, basin	h, lab.	h, analyt	h, num.
-	-	[°Ch]	-	[mm]	[mm]	[mm]	[mm]
1	LI	50	w.	-	8	6	6
			w.-eth.	20	9	8	8
2		101	w.	-	12	12	11
			w.-eth.	20	16	15	15
3		62	w.	-	8	7	7
			w.-eth.	20	9	9	10
1	CL	50	w.	-	23	17	11
			w.-eth.	15	27	20	16
2		101	w.	-	50	34	26
			w.-eth.	40	48	39	36
3		62	w.	-	23	21	14
			w.-eth.	25	27	24	21

For the considered scale of experiments, the higher value of the heat flux coefficient will give around 30 % faster growth for laboratory conditions than for ice tank. For example, for 50 and 100 FDD level ice thickness would be 7.5 mm instead of 5.8 mm and 14.7 mm instead of 11.5 mm. Measured in laboratory conditions consolidated layer thickness was 27 mm and 48 mm for ethanol solution and the same freezing indexes (Table 2). These values are larger than temperature sensor spacing of 13 mm so we can expect to measure ice thickness in the basin experiment with a reasonable accuracy (Figure 2).

Ice thickness estimation and ice structure

For large scale experiments indirect thickness estimation from the vertical temperature profile is a trivial process due to a significant temperature difference between ice top and bottom surfaces. For smaller scales, the most of temperature changes are occurring in the air inside thermal boundary layer. The thickness estimation from the temperature profile is limited by temperature sensors spacing. For the accurate estimation of freezing rates this problem was approached for the more controlled laboratory experiments.

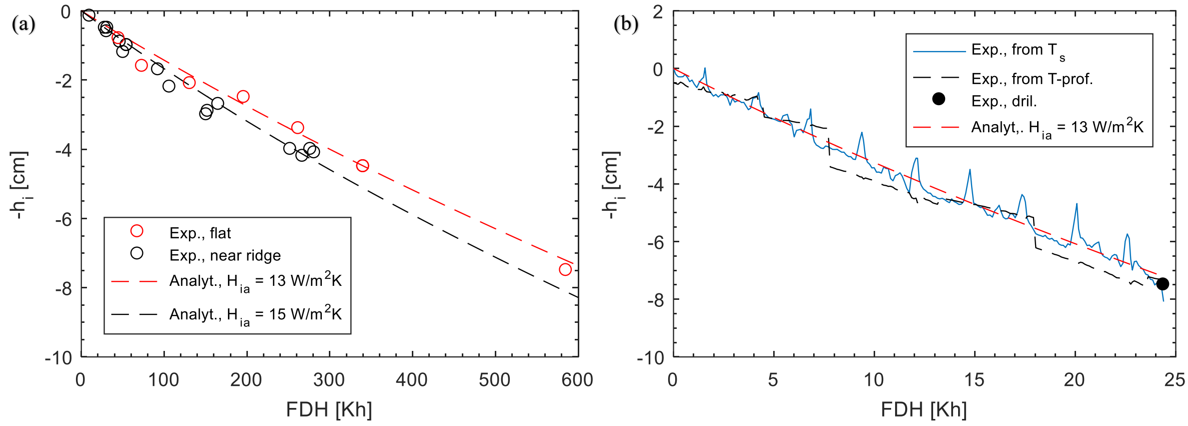

Figure 1. Freshwater level ice thickness vs FDH for NTNU laboratory experiments with different surface roughness using direct thickness measurements (a) and from different thickness estimation algorithms during single experiment (b).

Assuming constant value of the heat transfer coefficient it is possible to estimate ice thickness from its measured surface temperature for almost any thickness range (Figure 1b). Examples of temperature profiles for 50 and 100 FDH at the end of experiments are presented in Figure 2. It shows the difference between temperatures in the ridge voids and blocks, that can lead to the thickness overestimation of approximately 2 cm for the block profiles.

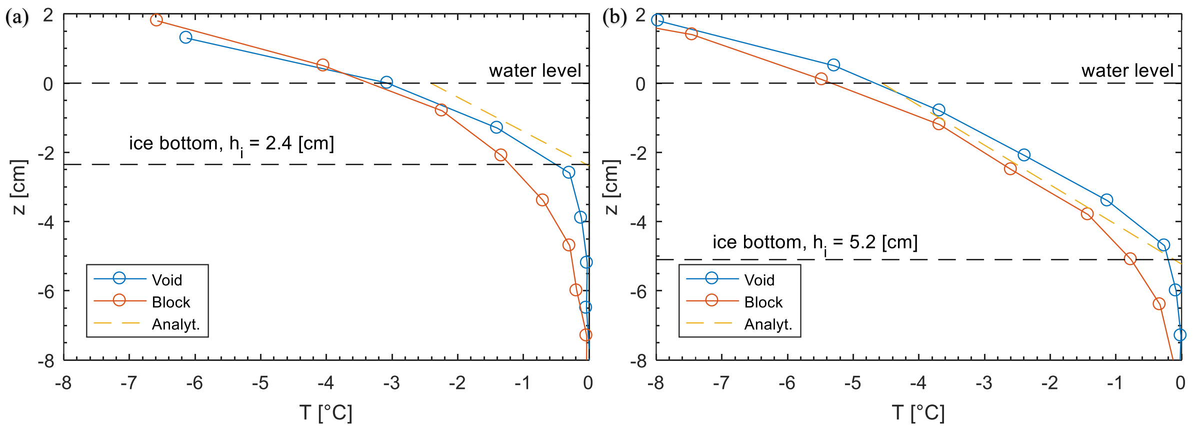

Figure 2. Temperature profiles of freshwater ridges at the end of laboratory experiments with

50 FDH (a) and 100 FDH (b).

We performed a comparison of level ice growth from freshwater and from 0.3 % ethanol solution in identic thermal conditions. It was found that ethanol ice is growing approximately 15 % faster than freshwater ice (Figure 3a). This difference was close to the difference between saline and fresh ice growth based on our numerical model for 0.3 % salinity for both liquid and solid parts.

Additionally, ethanol ice has a dendritic structure with dendrites occupying approximately 50 % of the total ice thickness, while freshwater ice has a planar thermodynamically stable interface. The same ice structure was nor observed during experiments with ethanol ridges: consolidated layer did not have a large layer of dendrites. According to the performed thin sections and similarly to the numerical simulations ice growth in ridges occurs mostly in a horizontal direction, allowing to overcome supercooled layer of liquid.

Values of consolidated layer thickness as a function of FDH from experiments and from our numerical model is shown in Figure 3b. We have not found any significant difference in consolidation rates between freshwater and ethanol ridges based on our laboratory results. Both ridges produced from warm (-1 °C), and cold (-15 °C) blocks were freezing close to the results of our analytical and numerical models.

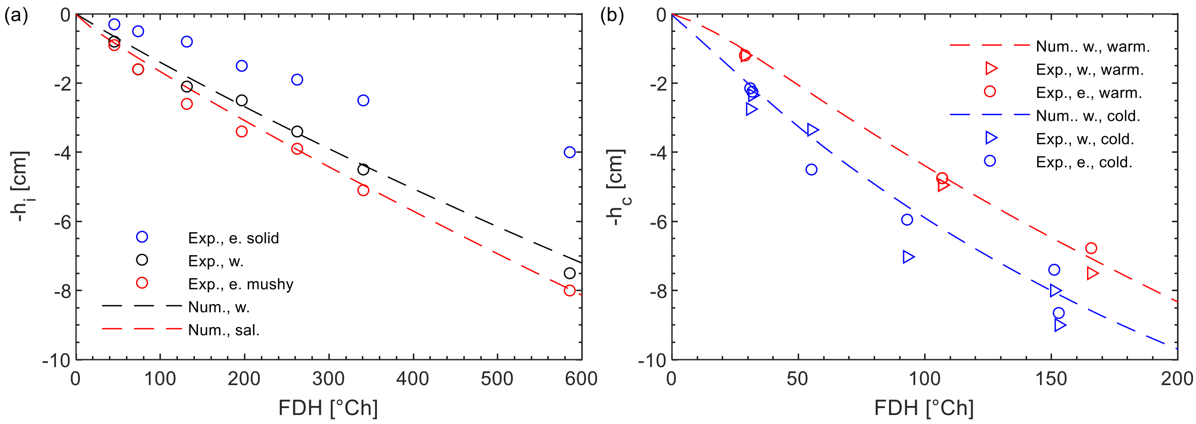

Figure 3. Level ice (a) and consolidated layer thickness (b) vs FDH for experimental, analytical, and numerical experiments.

The experiments with warm blocks can be well described by analytical solution even for larger scales. For the cold blocks consolidated layer thickness is usually underestimated analytically for the initial stages of experiments and overestimated for the larger scales (Figure 4a).

The results of laboratory experiments for cold blocks can be only explained if some part of initial block sensible heat goes not to porosity change but to consolidated layer growth (Figure 4b). For the analysis we used two factors: ratio of consolidated layer and level ice thickness $R = h_c/h_i$ and corresponding normalized factor R_n defined as (Salganik et al., 2020):

$$R_n = \left(\frac{h_c(h_c + 2k_i/H_{ia})}{h_i(h_i + 2k_i/H_{ia})} \eta_0 \right)^{0.5} \quad (3)$$

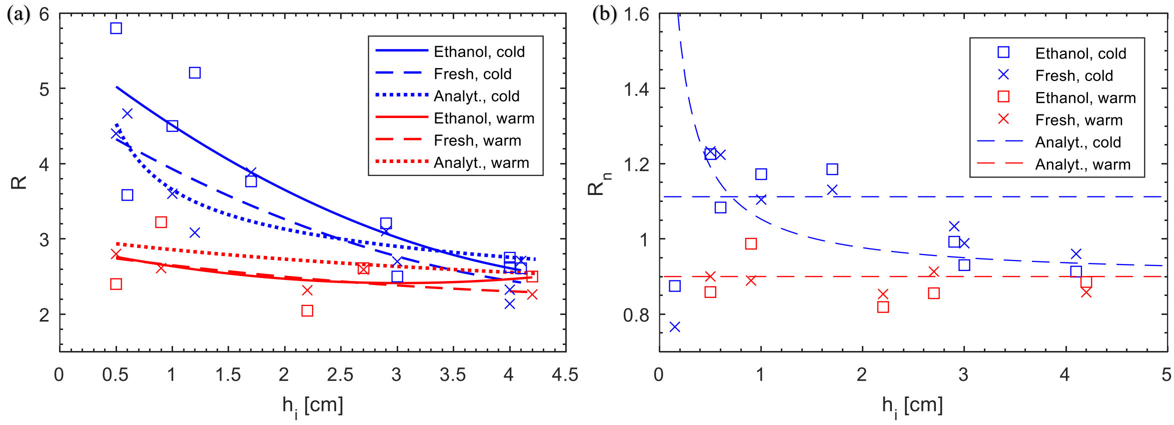

Figure 4. R (a) and R_n (b) factors vs level ice thickness from the lab. experiments and from analytical solution.

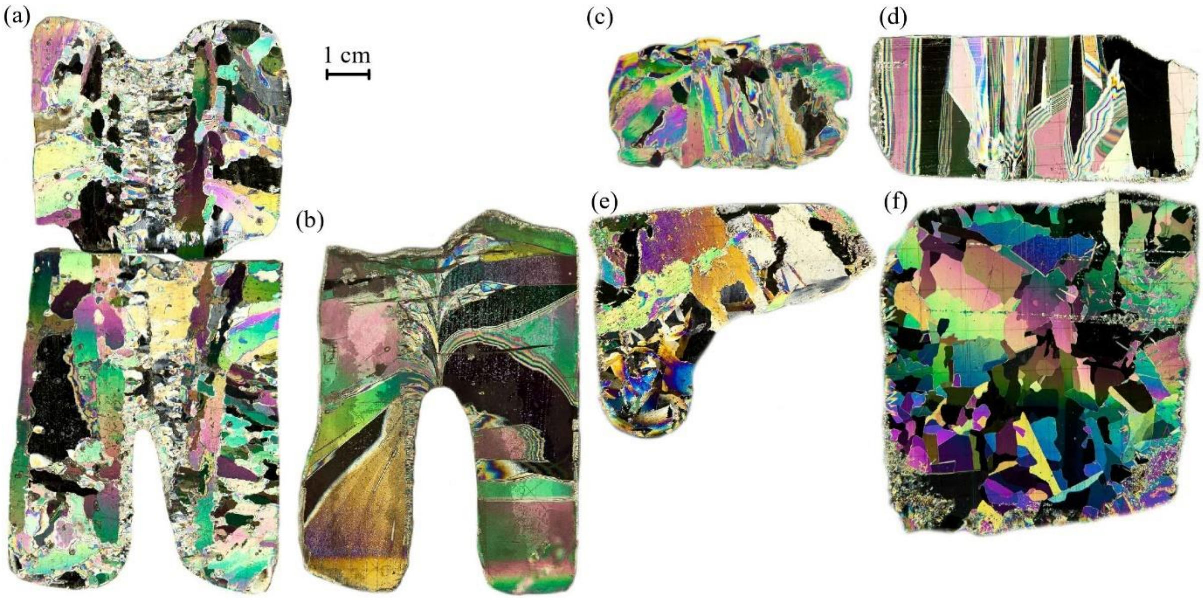

Figure 5. Vertical thin section of ethanol ridge (a), freshwater ridge (b), ethanol level ice (c), freshwater level ice (d), horizontal thin section of ethanol level ice (e), freshwater level ice (f).

Grain size was estimated using thin sections presented in Figure 5. Freshwater level ice had grains around 5 mm, ethanol level ice had slightly smaller grains of 4 mm. Newly formed ice in consolidated layer had much finer grains around 1 mm for both freshwater and ethanol ridges.

Results of basin test experiments

Temperature profiles were measured in the model ice produced by spraying. Its directly measured thickness was in the range of 40–45 mm. Temperature profiles in that ice confirms those values. During the end of consolidation time there was a thin layer of supercooled water under the old level ice, which disappeared after the start of warming phase.

Estimated from temperature profile consolidated layer thickness is 20 mm for floe 1, 40 mm for floe 2 and 25 mm for floe 3.

Table 3. Measured and estimated ice thickness for basin tests [mm]

Ice type / Ice floe	Floe 1	Floe 2	Floe 3
New LI	22 / 20 (T)	20 (T)	20 (T)
Old LI	41-45	40-41 / 35 (cam.)	40-42
CL	15 / 20 (T)	40 / 40 (T)	25 / 25 (T)

Thickness values of different ice types measured directly, estimated from camera photos (cam.) and from temperature profiles (T) are presented in Table 3. Those measured and estimated thickness values are in a good agreement with the results of numerical modelling (Table 2).

DISCUSION

Basin tests with ice-structure interaction are providing unique chance to have a scaled experiment with load measurements. But there are many uncertainties in ridge morphological parameters, which can make analysis of the interaction in comparison to the full scale complicated. One of these parameters is a thickness of consolidated layer. Laboratory experiments validated with analytical and numerical modelling were performed to provide more accurate predictions of consolidation rates for similar conditions to the performed basin experiment.

Measurements of consolidated layer thickness for ridges produced in ice basins includes a lot of uncertainties due to the high ratio of measuring methods errors and ranges of thickness. Direct measurements are almost impossible because basin scale ridge from ethanol ice is too fragile so it cannot be elevated from the liquid. Model ice is also not providing enough resistance to perform ice drilling suitable for the ridge profiling.

Temperature profiles can also be used, but their measurements could be influenced by several factors: local sail height, local keel depth and vertical position of thermistor. Both sail and keel underestimation can lead to an overestimation of the consolidated layer thickness.

Another important value which is hard to measure with a good precision is a ridge macroporosity. For our basin tests it was estimated from the cross-sectional profiles of keel depth, average sail height and initial ice volume before ridge production. Tuhkuri (2002) showed a large variability of ridge macroporosity values for similar ridging conditions in Aalto ice basin.

SUMMARY AND CONCLUSIONS

Thickness estimation of consolidated layer thickness can give only an idea of thickness range, but both accuracy and number of experiments is not enough to make a good correlation between freezing time and ice growth.

Additional laboratory experiments were performed to compare solidification of freshwater and ethanol level ice and ice ridges, to validate analytical and numerical models of ridge consolidation, and to provide more accurate thickness values for further analysis of basin test results.

Main results of the study can be summarized as:

- Laboratory experiments confirm a significant difference in temperature profiles in ridge voids and blocks, that can lead to thickness overestimation by the half block thickness.
- Validation of ridge consolidation model can be performed only in laboratory conditions with well-known key parameters including ridge macroporosity, heat transfer coefficient and position of thermistors.
- Level ice grown from 0.3% water-ethanol solution is growing 15% faster and has smaller grain size than level ice from pure water.
- Ice ridges grown from pure water and from water-ethanol solution have similar consolidation rate and similar grain size of newly formed ice.
- To keep the value of level ice flexural strength before consolidation, basin ice ridges must be warmed after the consolidation for approximately the same time.

REFERENCES

Ervik, Å., Nord, T.S., Høyland, K. V., Samardzija, I., Li, H., 2019. Ice-ridge interactions with the Norströmsgrund lighthouse: Global forces and interaction modes. Cold Reg. Sci. Technol. 158, 195–220. https://doi.org/10.1016/j.coldregions.2018.08.020

Griewank, P.J., Notz, D., 2013. Insights into brine dynamics and sea ice desalination from a 1-D model study of gravity drainage. J. Geophys. Res. Ocean. 118, 3370–3386. https://doi.org/10.1002/jgrc.20247

Notz, D., 2005. Thermodynamic and fluid-dynamical processes in sea ice. University of Cambridge.

Salganik, E., Høyland, K.V., Maus, S., 2020. Consolidation of fresh ice ridges for different scales. Cold Reg. Sci. Technol. 171. https://doi.org/10.1016/j.coldregions.2019.102959

Salganik, E., Høyland, K.V., Shestov, A., 2021. Medium-scale experiment in consolidation of an artificial sea ice ridge in Van Mijenfjorden, Svalbard. Cold Reg. Sci. Technol. 181. https://doi.org/10.1016/j.coldregions.2020.103194

Shestov, A., Ervik, Å., Heinonen, J., Perälä, I., Høyland, K.V., Salganik, E., Li, H., van den Berg, M., Jiang, Z., Puolakka, O., 2020. Scale-model ridges and interaction with narrow structures, Part 1 Overview and scaling, in: Proceedings of the IAHR International Symposium on Ice. Trondheim, Norway, pp. 306–315.

Tests, M., Predictions, F.S., Wake, F.S., Factors, M.C., Data, I., Data, O., Example, T., Analysis, U., With, C., Scale, F., 1999. ITTC – Recommended Procedures ITTC – Test Methods for Model Ice Properties. ReVision.

Timco, G.W., 1986. EG/AD/S: A new type of model ice for refrigerated towing tanks. Cold Reg. Sci. Technol. https://doi.org/10.1016/0165-232X(86)90032-7

Timco, G.W., Goodrich, L.E., 1988. Ice rubble consolidation. Proc. 9th Int. Symp. Ice, Int. Assoc. Hydraul. Eng. 1, 537–548.

Tuhkuri, J., 2002. Laboratory tests on ridging and rafting of ice sheets. J. Geophys. Res. 107, 1–14. https://doi.org/10.1029/2001jc000848

von Bock und Polach, R., Ehlers, S., Kujala, P., 2013. Model-scale ice - Part A: Experiments. Cold Reg. Sci. Technol. 94, 74–81. https://doi.org/10.1016/j.coldregions.2013.07.001