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Thermodynamics and Consolidation of Ice Ridges for Laboratory Scale

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ABSTRACT

First-year ice ridge interaction with structures often gives highest loads and can be modelled in controlled environment in ice basins. Five laboratory experiments were performed to study model-scale first-year ice ridge development. Effect of initial rubble temperature on consolidated level growth was observed. For both ridges with low and high initial rubble temperatures, consolidated layer was 2–4 times thicker than surrounding level ice at the initial phase of experiment. At the main phase of consolidation this ratio approaches lower equilibrium value of 1.2–1.7 of level ice thickness that is also depends on initial rubble temperature. Non-linear sea ice specific heat capacity can change consolidation development that results in sufficient difference from ice thickness prediction using Leppäranta (1993) and Ashton (1989) approaches.

Observed ratios of air, ice top and bottom surface temperatures can be used for consolidated layer thickness predictions in laboratory conditions using obtained heat transfer coefficient H_{ia}.

During the main phase vertical conductive heat flux at the top of consolidated layer was about two times higher than heat flux at the bottom part due to sea ice cooling. Latent heat flux was slightly lower than vertical conductive heat flux at the bottom of consolidated layer due to natural water convection.

Consolidated layer bulk salinity was always lower than salinity of surrounding level ice for provided experiments. This difference was becoming larger after melting phase.

This study can be approach for better understanding of the main differences between thermodynamics of model-scale and full-scale ice ridges.

KEY WORDS: Ice, ridges, thermodynamics, consolidation, laboratory.

INTRODUCTION

Increasing level of transportation and exploration in the Arctic enhance the significance of ice loads on coastal and offshore structures. Loads from ice ridges often give highest quasi-static loads. In contrast with level ice, loads from ice ridges depends on several that are hard to measure directly in field.

The thickness of consolidated layer h_c is one of these and because of uncertain data the load estimation may become inaccurate. Analysis of mesoscale experiments requires good understanding of aspect ratio effect on stress distributions. However, it is possible to model ice-structure interaction with controlled key parameters in ice basins.

Mechanical scaling traditionally involves decreasing of both ice strength and elastic parameters. This originates from studies of icebreakers advancing through level ice where inertia and gravity forces both play key roles. It is not obvious that the gravity contribution is necessary for relatively slow interaction between ice ridges and fixed structures. One of the main problems connected to mechanical scaling is that in vicinity of the melting point not only strength and elastic parameters are changing but also mechanisms of ice failure and applicability of elastic material model.

Thermodynamics of ice ridge governs both the thickness and the strength of consolidated layer, two key parameters for ice ridge load determination: ISO/FDIS/19906 (2010) recommends modelling the consolidated layer of ice ridges as thick level ice, even though it may have different salinity, ice texture and temperature profile.

Laboratory experiments were provided to understand how controlled consolidation parameters (air and water temperature, initial ice temperature, dopant fraction and time) could affect both consolidated layer thickness and salinity for laboratory scale.

The main goal of this study is to investigate ridge consolidation process because ratios of different thermal processes (conduction, convection, solidification, salt expulsion and initial rubble sensible heat at temperature T_0) is different for different scales while laboratory scale is used for basin tests and full scale is used for collecting and verification of ice ridge thermal, mechanical and geometrical parameters.

RIDGE CONSOLIDATION THEORY

Full-scale ridge development usually consists of three main phases: initial, main and decay (Høyland and Liferov, 2005). For laboratory scale, initial phase (when ice rubble temperature T_0 is lower than freezing point of surrounding water T_f) can continue during significant part of the whole experiment time (Chen and Høyland, 2016). For adiabatic conditions, realized in an ice rubble, the change of initial keel macro-porosity $\Delta\eta$ for fresh ice is equal to:

$$\Delta\eta = (1-\eta)\frac{c_i\left(T_f - T_0\right)}{L_i} = (1-\eta)Ste, \tag{1}$$

where η is the initial rubble macro-porosity, c_i is the fresh ice specific heat capacity, L_i is the latent heat of ice, Ste is the Stefan number.

Change of keel macro-porosity $\Delta\eta$ for saline ice is higher due to change of ice micro-porosity during temperature change and so that strongly depends on freezing temperature of surrounding water (Schwerdtfeger, 1963):

$$\Delta\eta = (1-\eta)\frac{\int_{T_0}^{T_f} c_{si}(T)dT}{L_{si}}, \tag{2}$$

where c_{si} is the sea ice specific heat capacity, L_{si} is the latent heat of sea ice.

Heat convection in the water initiated by solidification can decrease saline ice growth rate providing heat flux around 280 W/m^2 in the beginning of initial phase and around 90 W/m^2 in the late phase for ice initial temperature of 35°C (Chen and Høyland, 2016). That corresponds to heat transfer coefficient H_{iw} of 8 W/m^{2}K for the initial phase.

Forced and natural air convection affects consolidation rate by governing ice top surface temperature T_s depending on ice thickness h and ice surface roughness, air temperature T_a and circulation, and water freezing temperature T_f. Biot number represents ratio of conduction resistance within a solid ice to the external convection resistance offered by the surrounding air (Bergman, et al., 2011):

$$Bi = \frac{H_{ia}h}{k_i} = \frac{T_f - T_s}{T_a - T_s}, \tag{3}$$

where H_{ia} is the heat transfer coefficient, h is the ice thickness, k_i is the ice thermal conductivity.

Recommended values of heat transfer coefficient H_{ia} are in the range of 10–30 W/m^{2}K for still air and 6.7 m/s wind speed correspondingly (Ashton, 1989).

Ice thickness under assumption of linear temperature profile and no water convection can be calculated from the top ice surface T_s and the water freezing temperature T_f as (Stefan, 1891):

$$h(t) = \sqrt{h(t_0)^2 + \frac{2k_i}{\rho_i L_i}\int_{t_o}^{t}(T_f - T_s)dt}, \tag{4}$$

where k_i is the ice thermal conductivity, ρ_i is the ice density, L_i is the latent heat of ice.

The surface temperature T_s can be significantly higher than the air temperature T_a for thin ice growth. Under assumption of equal convective heat flux to the atmosphere and conductive heat flux through the ice Ashton (1989) derived an equation for the ice thickness, based on values of air temperature T_a, water freezing point T_f, and heat transfer coefficient H_{ia}:

$$h(t) = \sqrt{\frac{2k_i}{\rho_i L_i}(T_f - T_a)t + \left(\frac{k_i}{H_{ia}}\right)^2} - \frac{k_i}{H_{ia}} \tag{5}$$

Consolidated layer growth can be calculated assuming reduced value of the ice latent heat multiplied by the value of macro-porosity η (Leppäranta, 1993):

$$L_c = \eta L_i \tag{6}$$

This equation is valid only under assumption of constant macro-porosity in the ridge keel part that will consolidate.

EXPERIMENTAL SETUP

A series of laboratory experiments were performed with different initial rubble temperature and different thermal boundary conditions: 2D and 3D configurations (Figure 1). One vertical layer of ice rubble partly insulated from sides and from the bottom by acrylic walls was used at 2D configuration. Plastic net with 30x30 cm horizontal cross-section was filled with ice rubble at 3D configuration. Two sides of the plastic net were thermally insulated during run 4 and there was no insulation of model ridge at run 5.

Ice for model ridges was prepared in 1000 L water tank and cut into pieces of 8x4x4 cm (run 1, 2, 3 and 5) and 7x5x3 cm (run 4). Then transparent acrylic box (2D) or plastic net (3D) with ice rubble at initial temperature was placed in the middle of the tank with water at the freezing point. Two of the models (run 1 and 5) went through transition zone from consolidation to melting. Air temperatures were in the range of -(4–15)°C during initial and main phases of consolidation and around +5°C during decay phase. Amount of freezing degree-days ($FDD_{air} = \int (T_a - T_w)dt$) was in the range of 11–30°Cd. Initial water salinity $S_{w,0}$ was in the range of 20–34 ppt, rubble salinity $S_{i,0}$ was 3.8–7.0 ppt for different experiment runs.

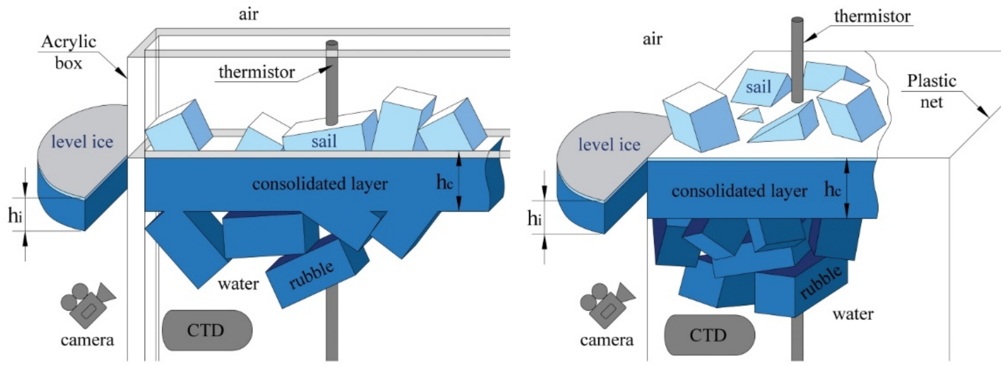

Figure 1. Experimental setup for 2D (left) and 3D (right) configurations

Thermistor strings and CTD (electrical conductivity, temperature and depth) sensors measured vertical temperature profile in air, consolidated layer, rubble, water, and water salinity and freezing temperature. Initial macro-porosity and consolidated layer thickness of 2D model ridges were obtained by underwater camera image processing. Freezing and upper surface temperatures of ridges were assumed equal to the temperature values measured by thermistor string at the bottom and the top surface of consolidated layer. Level ice thickness, water freezing temperature and salinity of water below level ice bottom surface were manually measured by ruler, thermometer (Ebro TFX 410-1) and conductivity meter (Mettler Toledo SG7-FK2).

Consolidated layer thickness was measured manually after each experiment. Initial macro-porosity of 3D model ridges was obtained from manually measured keel volume and number of rubble blocks. Evolution of consolidated layer and corresponding freezing temperatures were obtained from analysis of vertical temperature profiles from thermistors.

Two types of thermistor strings were used: 100 cm length thermistor string with metal cover and 15 cm length negative temperature coefficient thermistor string with plastic cover (Chen and Høyland, 2016).

After experiments, model-scale ridges were taken from water tank for geometrical, temperature, density and salinity measurements. Sea ice density ρ_{si} was measured by hydrostatic weighing in paraffin (Pustogvar and Kulyakhtin, 2016).

RESULTS

Key initial parameter's values and experiment results after a main consolidation phase are presented in Table 1. The ratio of consolidated layer h_c and level ice thickness h_i is called degree of consolidation $R = h_c/h_i$. It can be estimated from experimental data and also can be derived using Stefan's predictions $R^{Ste} = h_c^{Ste}/h_i^{Ste}$ based on measured consolidated layer surface temperatures and initial macro-porosity of consolidated layer η.

For lower rubble initial temperature for both 2D and 3D experiments give higher degree of consolidation in comparison to Stefan's predictions. Average values of heat transfer coefficient

H_{ia}, derived from consolidated layer top and bottom surfaces and air temperatures using equation (3), were higher for experiments with colder initial rubble. At the same moment heat transfer coefficient H_{ia}, based on direct level ice thickness and air temperature values, was around 20 W/m^{2}K for all provided experiments.

Table 1. Consolidation experiments summary

N	Type	T_0	η	$\Delta\eta$	$S_{i,0}$	$S_{w,0}$	FDD_{air}	H_{ia}	h_i	h_i^{Ste}	h_c	h_c^{Ste}	R	R^{Ste}	R/R^{Ste}
-	-	°C	-	-	ppt	ppt	°Cd	W/m^{2}K	cm	cm	cm	cm	-	-	-
1	2D	-2.7	0.41	0.20	7.0	20.2	15.4	7.0	6.5	4.2	7.5	6.6	1.15	1.57	0.73
2	2D	-7.9	0.49	0.25	7.0	22.0	11.0	15.0	4.6	6.1	8.0	8.7	1.74	1.43	1.22
3	2D	-6.4	0.38	0.25	7.0	24.1	29.3	22.0	9.5	13.7	12.9	20.5	1.36	1.50	0.91
4	3D	-17.6	0.47	0.21	5.0	24.0	15.1	20.0	9.0	9.3	11.9	13.6	1.32	1.46	0.90
5	3D	-3.0	0.31	0.04	3.8	34.2	29.5	7.0	13.5	18.1	18.0	32.3	1.33	1.78	0.75

Both ice top and bottom surface temperatures of consolidated layer are different from level ice temperatures due to different ratios of conduction and convection, and due to different growth rate and salt expulsion for 2D and 3D configurations. Consolidated layer average vertical temperature gradient was almost constant during experiment time while values of the gradient were significantly higher at the top ice surface than at the bottom surface. For typical vertical temperature profile, the air temperature was significantly lower than ice top surface temperature while ice bottom temperature was slightly lower than water temperature below (Figure 2).

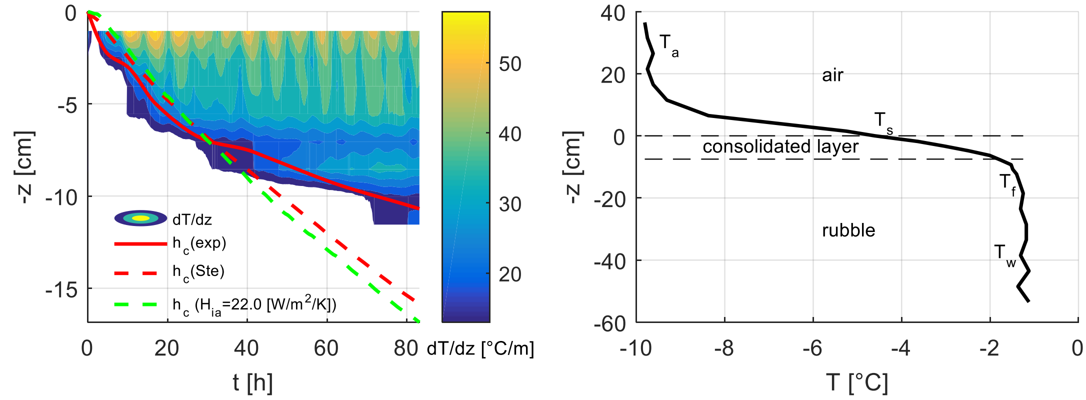

Figure 2. Temperature and temperature gradients in time and space: a) Vertical temperature gradient dT/dz vs time t and water depth z. Red solid curve is h_c from video analysis, red dashed curve represents h_c prediction from Stefan's equation and green dashed curve represents h_c prediction from Ashton's equation using heat transfer coefficient of 22 W/m^{2}K and b) temperature profile of model ridge after t = 40 h (right) for run 3 (2D)

Macro-porosity measurements are complex for volumetric (3D) ice ridges while image processing can give its values for planar (2D) consolidation experiments. Initial macro-porosity vertical distribution is important for ice growth analysis and its values could have significant deviations from average values. Without taking into account low values at the box corners macro-porosity for run 3 was in the range of 0.12–0.26 (Figure 3).

For thin ice growth, difference between air and water freezing temperature is usually much higher than difference between ice top and bottom surface temperatures. For provided experiments ratio between accumulated $FDD_{air} = \int (T_a - T_w)dt$ and $FDD_{ice} = \int (T_s - T_f)dt$ was in the range of 1.7–2.4 during experiments.

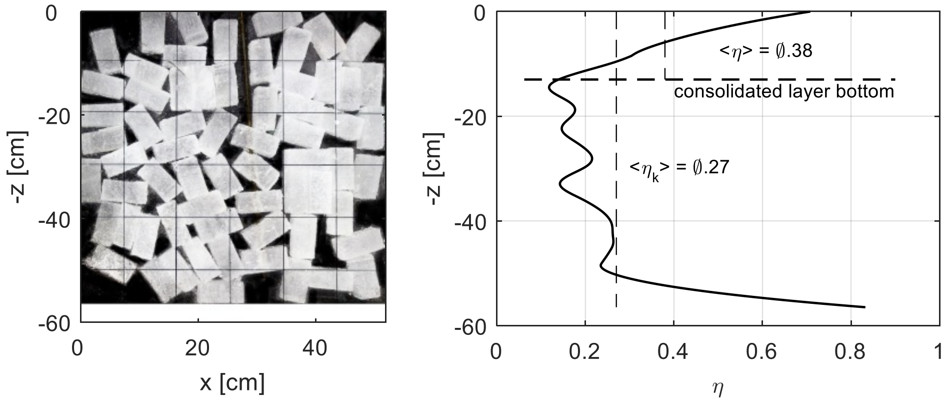

Figure 3. Initial rubble configuration (left) and macro-porosity distribution η vs water depth z (right) for run 3

Ratio of consolidated layer and level ice thicknesses, called degree of consolidation R, is a convenient way to represent ridge development. To neglect different ice growth rate for different macro-porosities η for different experiments and their stages, ratios of experimental and analytical degree of consolidation are presented at the Figure 4. Analytical values are based on Stefan's equation for ice growth, measured surface and water freezing temperatures and latent heat of fusion for consolidated layer $L_{i,c} = \eta L_i$.

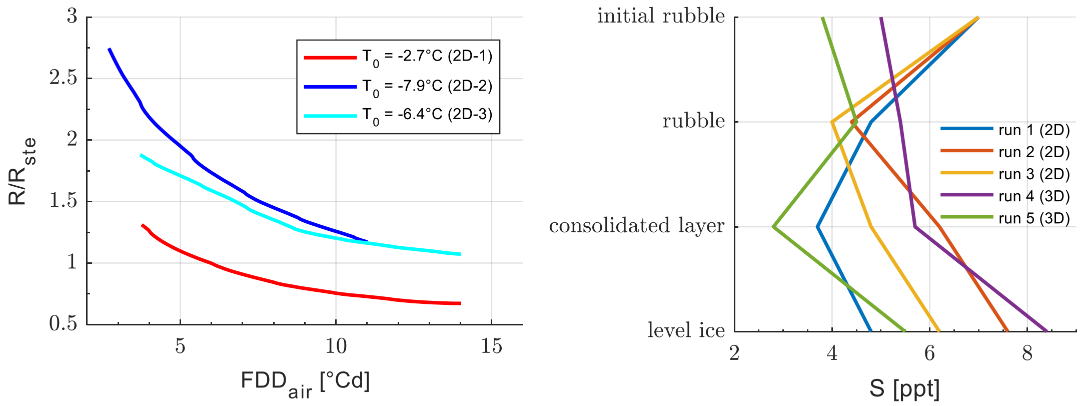

Figure 4. Ratio of experimental and analytical degree of consolidation vs FDD_{air} for 2D experiments with different initial rubble temperatures T_0 (left) and salinity of level ice, initial ridge rubble, consolidated layer and surrounding level ice (right)

Ice salinity usually depends on water salinity and ice growth rate. Consolidated layer was more saline than surrounding level ice (Figure 4). After decay phase, consolidated layer was becoming less saline than rubble and almost two times less saline than level ice. That means that ice consolidated layer had almost two times less micro-porosity than level ice around model ice ridge after the main phase. Bulk ice salinity was linearly decreasing during freezing.

Air content of sail is close to air content of consolidated layer top while air content of consolidated layer bottom is close to air content of rubble. Average air contents of level ice and consolidated layer are close. Density of model ridge rubble was slightly lower than density of level ice and consolidated layer.

DISCUSSION

After short time of consolidation, less than 5°Cd, consolidated layer thickness was almost 2 times higher than thickness value predicted only by initial rubble macro-porosity in comparison to level ice thickness (Figure 4). This effect was decreasing in time, and consolidated layer thickness started approaching equilibrium value that also depends on initial rubble temperature. For initial rubble temperatures close to water freezing point, this value is around 0.7 for both 2D and 3D experiments. For lower initial temperatures values of R/R^{Ste} are higher for 2D configuration than for 3D.

It is possible to estimate change of initial macro-porosity $\Delta\eta$ based on values of the rubble initial temperature, the sea ice specific heat capacity, the sea ice latent heat and initial rubble porosity η using equation (2). Ratio of R/R^{Ste} can be estimated from macro-porosity as:

$$\frac{R}{R^{Ste}} = \sqrt{\frac{\eta}{\eta - \Delta\eta}} \tag{7}$$

It is assumed that heat diffusion in the rubble is fast enough to form new ice before consolidated layer significant growth. For provided experiments, values of estimated ratios of R/R^{Ste} were in the range of 1.1–1.7. However, this assumption cannot explain higher R/R^{Ste} experimental values during initial phase. It also does not account heat loss due to water convection and ice cooling that can explain slower ice growth at the late stages of experiments.

Two main processes govern consolidated layer growth rate: extraction of initial sensible energy $\int cdT$ due to temperature increase and upper surface cooling by air convection. First process strongly depends on ice rubble salinity. New ice is forming faster around fresh ice (for several hours depending on ice rubble size) but saline ice can store higher amount of energy to form new ice around it due to non-linear sea ice specific heat capacity c_{si} and sea ice thermal conductivity k_{si}. Fourier number can be used for dimensionless analysis of described heat transfer.

Second governing process is consolidation due to cooling from above. This process also depends on ice salinity because for high values of saline ice specific heat capacity significant amount of heat should be spent on sea ice cooling so less heat can be available for ice formation. It can be seen from non-linear ice vertical temperature gradient profile during provided experiments.

Cooling can decrease effect of initial macro-porosity change because ice at freezing temperatures of surrounding contains sufficient amount of brine that should be partly frozen after cooling. It should be said that for engineering or basin test application consolidated layer thickness at the air temperature equal to the surrounding water freezing temperature is a value of interest. It is also a convenient value for experimental analysis because all the energy stored in initial rubble should be spent on consolidation process not on cooling.

Another complication of consolidated layer formation analysis is the effect that due to lower permeability and slow solute diffusion water salinity near consolidation surface is significantly higher than initial water salinity that leads to less amount energy that could be extracted from cold rubble.

According to Chen and Høyland (2016) for ice surrounded by fresh water, amount of new formed fresh ice around saline ice $\Delta V/V$ is 48 % higher than for fresh ice: 26 % and 16 % respectively. This value corresponds to the volume change $\Delta V/V$ calculated from sea ice specific heat capacity values by Schwerdtfeger (1963) including total melting of initial saline ice:

$$\frac{\Delta V}{V} = \frac{\int_{T_0}^{T_f} c_{si}(T)dT}{L_i} = \frac{\int_{-35}^{-0.13} c_{si}(T)dT}{L_i} = 1.34, \quad (8)$$

where $T_f = -0.13°C$ is the freezing temperature of sea ice with salinity of 2.65 ppt.

The test results prove that initial rubble temperature changes not only initial degree of consolidation values but also its values during cooling. This degree of consolidation value depends on ratio of initial rubble temperature and consolidated layer temperature at the end of experiment. It can be confirmed by the fact that degree of consolidation values after decay phase (when consolidated layer temperature is close to water freezing point) were approaching $1/\sqrt{\eta}$ values (and $R/R^{Ste} = 1$) for experiments with high rubble initial temperature.

For experiment runs 2 and 3 with rubble initial temperatures of -7.9°C and -6.4°C degree of consolidation values are approaching values $1/\sqrt{\eta}$ because these temperatures are relatively close to final consolidated layer surface temperatures of -4.0°C and -5.4°C respectively.

These assumptions can explain why consolidated layer growth is faster at the beginning and slower after initial phase (Figure 2).

During the main phase vertical conductive heat flux at the top of consolidated layer $(k_{si}dT/dz|_{z=0+})$ is about two times higher than heat flux at the bottom part $\left(k_{si}dT/dz|_{z=h_c-}\right)$ while this difference accounts for ice cooling. Latent heat flux $(\rho_{si}L_{i,c}\, dh_c/dt)$ is at the same moment slightly lower than vertical conductive heat flux at the bottom of consolidated layer. This difference accounts for water convection that is not considered at Stefan's condition:

$$\rho_{si}L_{i,c}\, dh_c/dt = k_{si}dT/dz|_{z=h_c-} \quad (9)$$

Lower initial rubble temperature also leads to higher ratio of conduction resistance to the external convection air resistance. While thin level ice growth is governed by air convection, consolidated layer growth is also controlled by initial sensible energy. However, for full-scale first-year ice ridges difference between sail surface temperature and air temperature is insignificant (Shestov and Ervik, 2016).

2D experiments give easily accessible data of macro-porosity distribution that is very valuable for consolidation analysis. 3D configuration provides realistic thermal boundary conditions with insulation along imaginable model ridge axis, without insulation at water-keel boundaries and realistic permeability of rubble. There is no perfect insulation at ridge sides for 2D configuration. It creates addition heat fluxes oriented not in vertical direction. Permeability difference leads to higher difference in level ice and consolidated layer bottom surface temperatures due to higher water bulk salinity around rubble inside 2D box.

Consolidated layer bulk salinity was always lower than salinity of surrounding level ice. This difference was becoming larger after melting phase. It could be critical for scale-model mechanical experiments because ice strength is governed by salinity and temperature while thinner level ice is more saline and its temperature have to decrease faster than for thicker consolidated layer.

CONCLUSIONS

Five laboratory experiments were performed to study model-scale ridge development. Effect of initial rubble temperature on consolidated level growth was observed during initial and main phases of ridge formation. For both ridges with low and high initial rubble temperatures, consolidated layer was 2–4 times thicker than surrounding level ice at the initial phase of experiment. At the main phase of consolidation this ratio approaches lower equilibrium values in the range of 1.2–1.7 that is also depends on initial rubble temperature. Effect of non-linear sea ice specific heat capacity on degree consolidation was described in order to explain sufficient difference from ice thickness prediction using Leppäranta (1993) and Ashton (1989) approaches.

Difference in ratio of conduction resistance within a solid ice to the external convection resistance offered by the surrounding air was observed for level ice and consolidated layer formed from a rubble of different initial temperatures. Observed ratios of air, ice surface and water freezing temperatures can be used for consolidated layer thickness predictions for laboratory conditions using obtained heat transfer coefficient H_{ia}.

During the main phase vertical conductive heat flux at the top of consolidated layer was about two times higher than heat flux at the bottom part due to ice cooling and high non-linear values of sea ice specific heat capacity. Latent heat flux was slightly lower than vertical conductive heat flux at the bottom of consolidated layer due to natural water convection.

2D and 3D experimental configurations and their advantages and potential method uncertainties of usage for consolidation process study were described.

Effect of different consolidation conditions for level ice and rubble was observed during experiments. Consolidated layer bulk salinity was always lower than salinity of surrounding level ice for provided experiments. This difference was becoming larger after melting phase that could be critical for scale-model mechanical experiments because ice strength is governed by salinity and temperature while thinner level ice is more saline and its temperature have to decrease faster than for thicker consolidated layer.

This study can be approach for better understanding of the main differences between thermodynamics of model-scale and full-scale ice ridges and for the development of ridge consolidation model. Future consolidation studies have to take into account main effects governing this process: air convection above ice surface, salt expulsion and diffusion below consolidated layer, initial sensible energy, macro-porosity distribution and non-linear specific heat capacity of sea ice during bulk salinity development.

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