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The Determination of Heat Transfer Coefficient on Water-ice Surface in a Free Convection

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ABSTRACT

In ice ridges consolidation, the convective heat flux term comes critical due to the larger contact areas and surface temperature differences compare with those from level ice. In this paper, a submerging experiment was designed to determine the heat transfer coefficient (h) between fresh ice and fresh water in a free convection. A thermistor string was used to measure temperature changes while ice growth was recorded by photograph. To study the factor, the tests were carried on different ice thickness (4.9cm to 20.5cm) and initial temperatures (-20°C and -32°C). The result shows that the h exponential increased with temperature difference from 0.3 W/m^{2}K to 175 W/m^{2}K. On the other hand, the variation of initial thickness and temperature was not a direct influence for *h*. For convective heat transfer, the boundary layer condition is central for understanding the convection between ice surface and water flowing past it. From the governing equation, the water flow in a free convection is caused by density difference, which is driven by the thermal expansion. A large temperature difference between surface and environmental water creates a thicker boundary layer, which leads to a higher *h*.

KEY WORDS: Heat transfer coefficient; Consolidation; Free convection; Ice.

INTRODUCTION

In Arctic seas, ice ridges is one of the major concerns for oil exploration and shipping. Compare with ice floe, ridges exist in a more complicated structure, which includes sail, keel and consolidated layer. From previous work, it is believed that the latter two parts make most contribution to the ice-induced load (Timco et al., 2000). In ISO19906 standard, the keel porosity and consolidated layer thickness are key parameters for ice loads prediction. To study the mechanical properties, one needs to understand the formation of the ridges structure, which varies through seas and areas (Høyland, 2007a; Leppäranta and Hakala, 1992). Under the driven of winds and currents, the ice floes may move against each other and be end of small pieces, which are called ice rubble (Hopkins et al., 1999; Leppäranta et al., 1995). In a further stage, the new ice freezes to fill the gaps and the ice rubble becomes consolidated (Høyland, 2002). During three phases of consolidation, the strongest ridges are believed to form within

the first two phases. In the study of Chen and Hoyland, the contribution of consolidation from the initial phase could be significant due to the saline properties (Chen and Høyland, 2016).

When the ice blocks fall into water, they experience a transient condition where the environment temperature is sudden changed. During this process, the cold ice is heated up by the energy released from phase change and convection, which is widely named oceanic flux. For the level ice, the oceanic flux varies in an order of 1-100W/m^2 and depends on the current condition (Høyland and Liferov, 2005; Leppäranta and Shirasawa, 2007; Shirasawa et al., 1997; Shirasawa et al., 2006). However, the water-ice temperature difference for level ice is much lower than that of a submerged ice. Mathematically, the convection is described by Newton's Law of cooling, which is a function of temperature difference and heat transfer coefficient. Therefore, this coefficient is critical in consolidation as well as its scaling since is it part of Biot number (Høyland, 2007b). Physically, the convection contains both conduction and advection, which is related to the fluid status(Bergman et al., 2011). When ice and water temperatures are closed, it is believed that the coefficient is a rather small value, which makes convection insignificant in level ice forming (Josberger, 1987; Leppäranta, 1993). However, the convection becomes essential under a large temperature gap, which leads to great thermal expansion and consequently fluid motion. Such a circumstance between water and ice has not been thoroughly studied.

In this paper, we designed and carried out a group of tests to investigate the heat transfer coefficient between ice and water in a free convection. To study the influence of initial condition, the experiments were done on varies thicknesses and initial temperatures.

THEORY

In this paper, the main purpose is to determine the heat transfer coefficient (h) between fresh water and fresh ice, where the ice block is submerged into water bath. To achieve this aim, related physical mechanism is needed to be understood in advance of experiments. Since the h is mainly associated with the boundary condition, which is dominated by the status of fluid for given solid and liquid material. It is reasonable to simplify the experiments to one-dimension.

Energy Contribution

When a cold ice piece falls into a water bath, where is much warmer than the ice, heat transfer starts under the driven of temperature difference. Such a case involves four energy contribution, which including conductive energy, convective energy, phase change energy and initial energy. Mainly, there is a warming up process inside the ice, where the inertial energy is increased by heat conduction. In the meantime, the heat from the warm water crosses water-ice surface, where ice freezing occurs. Among the energy terms, we are interested in the convection most since its association with heat transfer coefficient. However, it is very difficult to measure this part of energy directly. Therefore, in many studies, it is usually obtained by back calculation from energy conservation.

$$\Delta E_{in} = E_{lat} + E_{conv} \tag{1}$$

Where ΔE_{in} is the change of inertial energy; E_{lat} is the latent energy; E_{conv} is the convection energy.

$$\Delta E_{in} = \int_{T_0}^{T} mc_p dT = (T - T_0)\rho \cdot c_p \cdot L_0 \cdot A \tag{2}$$

Where T and T_0 are current and initial average temperature of ice block; L_0 is initial ice thickness; A is ice area exposed to water; ρ is density of ice; c_p is the specific heat capacity.

$$E_{lat} = \rho \cdot l \cdot \Delta L \cdot A \tag{3}$$

Where l is the latent hear; ΔL is the new ice thickness.

$$E_{conv} = (T_\infty - T_s) \cdot t \cdot A \cdot h \tag{4}$$

Where T_∞ is the water temperature; T_s is the temperature of ice at surface; t is time; h is the heat transfer coefficient.

Heat Transfer Coefficient

One way to study the heat convection is to find a solution of the correlation between thermal and velocity boundary layers. In this case, the governing equations of velocity layer is

$$u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = \frac{g\beta(T_s - T_\infty)}{u_0^2} T^* + \frac{1}{Re_L} \frac{\partial^2 u^*}{\partial y^{*2}} \tag{5}$$

On the left-hand side of equation, the two terms are net rate of momentum flow from control volume; on the other side, the terms are buoyancy and viscous forces. Where g is gravity acceleration, β is thermal expansion coefficient.

The governing equation of thermal layer is

$$u^* \frac{\partial T^*}{\partial x^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{1}{Re_L \cdot Pr} \frac{\partial^2 T^*}{\partial y^{*2}} \tag{6}$$

If we take $u_0^2 = g\beta(T_s - T_\infty)L$, then we get Grashof number (Gr_L)

$$Gr_L = \frac{g\beta(T_s - T_\infty)L^3}{v^2} \tag{7}$$

Where g is gravity accelerate; β is thermal expansion coefficient; L is characteristic length; v is viscosity. Gr_L is a measure of the ratio of buoyancy forces to the viscous forces and its expression is

Based on the Eq. (5) and Eq. (6), we expect a correlation:

$$Nu_L = \frac{hL}{k} = f(Gr_L, Pr) = C_1 \cdot Gr_L^{n_1} \cdot Pr^{n_2} \tag{8}$$

Where k is thermal conductivity, C_1, n_1 and n_2 are constants.

$$Pr = \frac{v}{\alpha} \tag{9}$$

Where v is viscosity, α is diffusivity.

Substituting Eq. (9), Eq. (7) into Eq. (8), we obtain the expression:

$$h = C_1 \frac{k}{L} \left(\frac{v}{\alpha}\right)^{n_2} \left(\frac{g\beta L^3}{v^2}\right)^{n_1} (T_s - T_\infty)^{n_1} \tag{10}$$

Where *h* is a function of thermal properties, length and temperature difference, as shown in Eq.10.

EXPERIMENTAL SETUP

In this section, we designed and carried experiments to represent a free convection in transient condition. To achieve this process, cold ice blocks were submerged into warm water bath (0.2°C above freezing point). From analysis in section 2.1, one needs to measure latent energy and inertial energy in order to determine the convection. During each test, the temperature was measured by thermistor strings while the ice growth was visually recorded.

Setup Overview

Based on the theoretical analysis above, a group of experiments was carried out in NTNU cold laboratory to model the thermal process. During each test, the ice growth was recorded by camera while the ice temperature was measured by a thermistor string. The further description is introduced by Chen and Hoyland.(Chen and Høyland, 2016)

a. The setup sketch   b. The setup photo
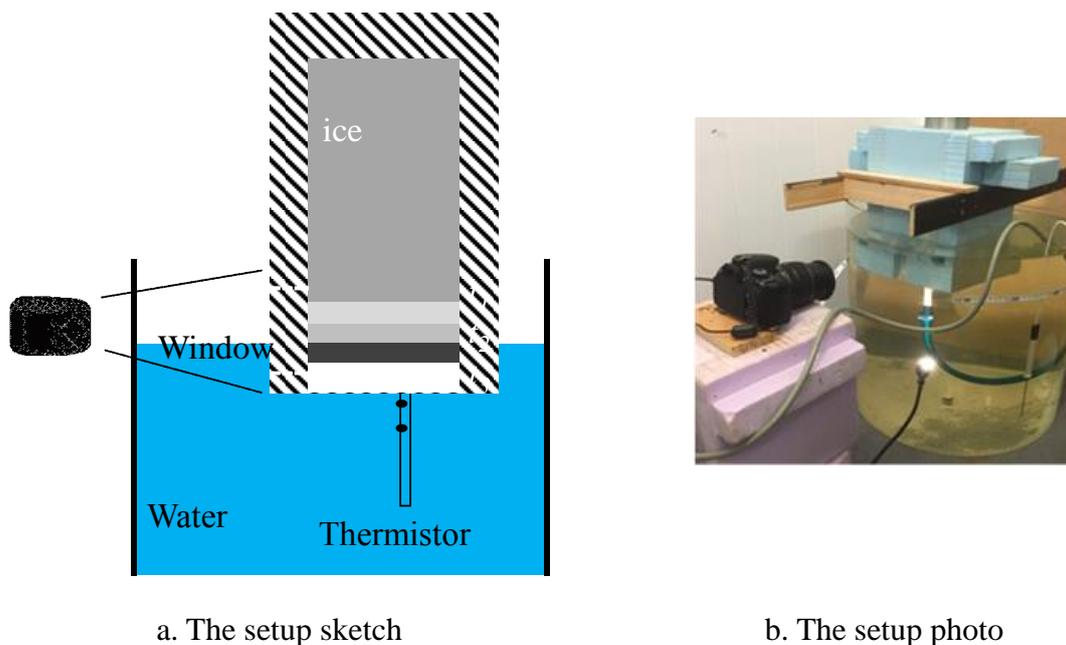
Figure 2. The overview of experiment setup

Experimental Matrix

In this work, the whole matrix is performed between fresh ice and fresh water. Since it is a model test, we are interested in size effect. Besides, the temperature different plays an important role in the coefficient. Therefore, the tests were done on the ice blocks with various initial temperatures and thicknesses as show in Table.1and Figure 3.
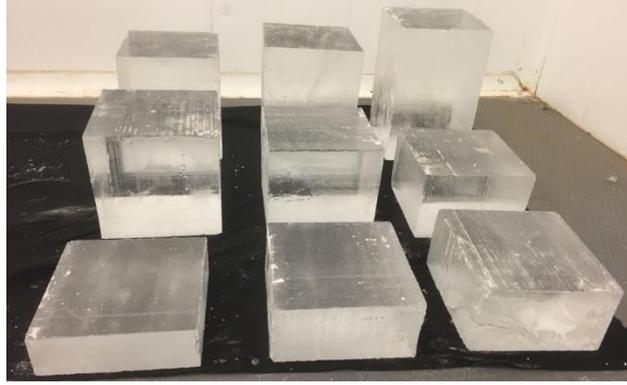
Figure 3. The ice samples with different thicknesses

Table 1. Experimental matrix

Experiment No.	Initial temperature (°C)	Initial thickness (cm)
01	-20±1	4.9±0.2
02	-20±1	6.4±0.2
03	-20±1	10.2±0.2
04	-20±1	20.5±0.2
06	-32±1	10.1±0.2

Determination of Heat Transfer Coefficient

As the derivation from Eq. (1)-(4), the coefficient can be back calculated as following.

$$h = \frac{\Delta E_{in} - E_{lat}}{(T_s - T_\infty) \cdot t \cdot A \cdot h} \qquad (11)$$

In Eq. (11), the thermal properties do not change significantly in our interested temperature range while ice geometry can be measured directly (Sharqawy et al., 2010). The temperature difference is the trickiest one not only in this case but also in most of transient conditions. Because it is almost impossible to properly deploy a sensor at the ice surface during its growing, we make a statement as following equation:

$$T_s = \left(\frac{T_1 - T_2}{d}\right)(d + \Delta L) + T_2 \qquad (12)$$

Where T1 and T2 are from two thermistors closest to the ice-water surface; d is the distance between neighboring sensors.

RESULT & DISCUSSION

As introduced in Sec.3, the temperature and thickness were hereby measured in each test.

Temperature

With the thermistor strings we built, it is able to see the temperature distribution within ice blocks. Figure 4 (a) shows the variation of temperature distribution of the sample with 10.2cm in thickness and -20°C in initial temperature. It is clear that the distribution had a non-linear beginning and linear ending. Therefore, it is a practical and reliable way to evaluate the surface temperature by the closest two sensor as we described in Sec 3.3.

In Figure 4 (b), the curves give us the information of averaged temperature. For each sample, the temperature climbed up due to the large temperature difference at beginnings and gently rose to freezing point. Since the thermal resistance is proportional to thickness, the warming up process proceeded slower in thicker ice samples. For instant, the curve from 4.9cm sample is steeper than that of 20.5cm sample. On the other hand, there was not much difference for the sample with lower initial temperature. For both samples with around 10cm thickness (10.2cm and 10.1cm), there is very little difference in the temperature curves.
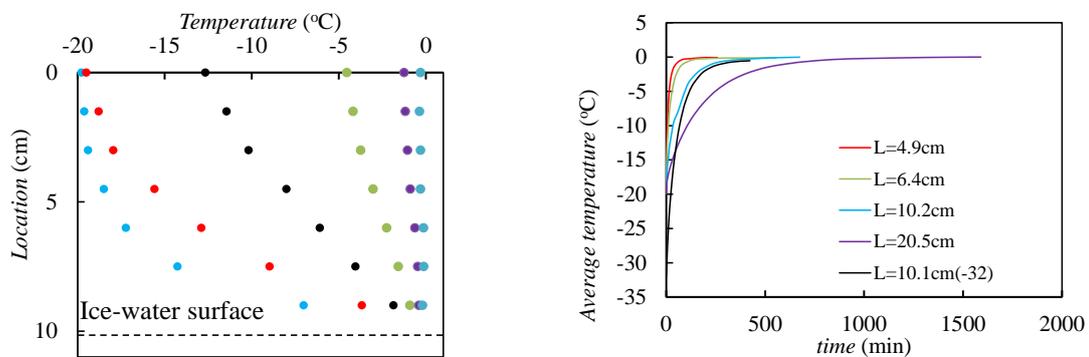
a. The temperature profile at 1st,5th, 30th, 100th, 200th, 500th minute (left to right)

b. The time series of average temperature

Figure 4. The temperature change of experiments

Ice Growth

The information of ice growth is given in Figure 5. The time series of thickness changes are plotted in (Figure 5 (a)), which is similar to the temperature, the ice grew faster at the beginning of each test and the growth rate slowed down until they reached the freezing point. That means, the temperature difference or gradient at the surface is the driven power to free new ice. Besides the common feature, the ice growth varied due to the different initial conditions. Apparently, there was more consolidation on colder and thicker ice pieces than others. It is because such samples has lower initial energy, which needs more energy to lift the temperature by freezing new ice.

If we leave a sight on the ratios between growth ice and initial ice as shown in Figure 5(b), the final percentage of thin and cold pieces are higher. Based on the energy conservation, the colder pieces absorb more energy, which is mainly released from consolidation. However, the convection leads to the difference for the samples with same initial temperature. For small ice block, the thermal resistance is smaller since it is a function of size and conductivity. Therefore, the test took longer time, which increased the convective part of energy. In another words, the small samples growth higher percentage since they obtained more energy from phase change rather than convection.

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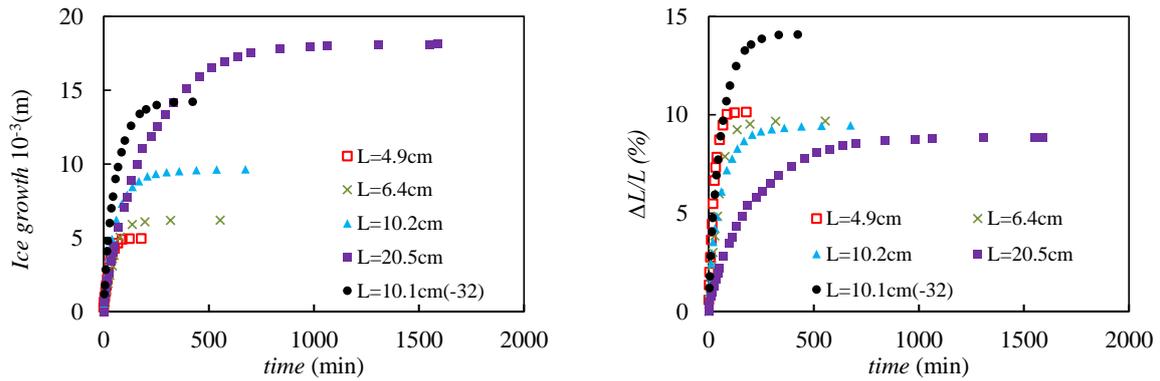
a. Time series of ice growth   b. Ratio between new ice thickness(ΔL) and initial ice thickness(L)

Figure 5. The ice growth

Heat Transfer Coefficient

Based on the data of thickness and temperature, the heat transfer coefficient is further calculated by Eq. (11). In the Figure 6, the relation between the coefficient and the temperature difference is plotted with both axis logged. Although the tests were done on varies initial conditions, it seems that those conditions did not lead to significant difference on the coefficient, neither thickness nor temperature. The only factor matters here is the temperature difference between ice surface and environmental water bath. This is because the convection is a combination of conduction and advection. While the conduction is mainly related to the material properties, the advection is dominated by the liquid motion. In our case, the water flow is driven by the thermal expansion, which is related with temperature difference. In other words, the temperature difference dominates the coefficient and hereby the convection. Furthermore, from the derivation in Sec.2.2 we learned that the coefficient exponential increase with temperature difference. From the equation of fitting curve, we can obtain the value of parameter n_1 in Eq.10, which is closed to 1.537.

$$\log(h) = 1.5368\log(T_s - T_\infty) - 0.719$$
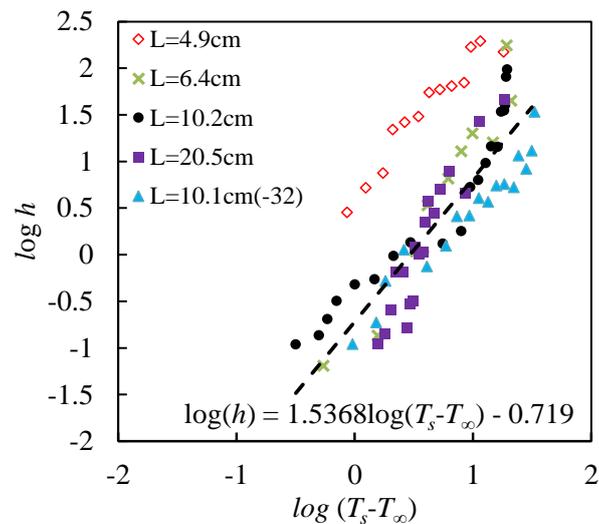
Figure 6. The heat transfer coefficient vs temperature difference

CONCLUSIONS

In this paper, a group of tests are done in NTNU cold laboratory to investigate the heat transfer coefficient of free convection. To represent the circumstance, an ice block was submerged into warm water bath. We varied the initial conditions of ice blocks to see their influences on the coefficient and conclude the information as following.

(1) When the ice is warming up, the thickness makes more influence to slow down the process than the initial temperature. (2) The initial temperature dominates the ice growth percentage while the thin ice grows slightly higher than thick ice. (3) The heat transfer coefficient is dominated by the temperature difference and independent with initial conditions. (4) The heat transfer coefficient exponentially increases with temperature difference and the power is 1.537.

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REFERENCES

Bergman, T.L., Incropera, F.P., DeWitt, D.P. and Lavine, A.S., 2011. Fundamentals of heat and mass transfer. John Wiley & Sons.

Chen, X. and Høyland, K.V., 2016. Laboratory Work on Heat Transfer in Submerged Ice, Theory, Experimental Setup and Results, Proceedings of the 23rd International Symposium on Ice (IAHR), pp. 4868615.

Hopkins, M.A., Tuhkuri, J. and Lensu, M., 1999. Rafting and ridging of thin ice sheets. Journal of Geophysical Research: Oceans, 104(C6): 13605-13613.

Høyland, K.V., 2002. Consolidation of first-year sea ice ridges. Journal of Geophysical Research: Oceans, 107(C6).

Høyland, K.V., 2007a. Morphology and small-scale strength of ridges in the North-western Barents Sea. Cold Regions Science and Technology, 48(3): 169-187.

Høyland, K.V., 2007b. Thermal scaling of ice ridges, some dimensionless numbers, Proceedings of the International Conference on Port and Ocean Engineering Under Arctic Conditions.

Høyland, K.V. and Liferov, P., 2005. On the initial phase of consolidation. Cold regions science and technology, 41(1): 49-59.

Josberger, E.G., 1987. Bottom ablation and heat transfer coefficients from the 1983 marginal ice zone experiments. Journal of Geophysical Research: Oceans, 92(C7): 7012-7016.

Leppäranta, M., 1993. A review of analytical models of sea-ice growth. Atmosphere-Ocean, 31(1): 123-138.

Leppäranta, M. and Hakala, R., 1992. The structure and strength of first-year ice ridges in the Baltic Sea. Cold Regions Science and Technology, 20(3): 295-311.

Leppäranta, M., Lensu, M., Kosloff, P. and Veitch, B., 1995. The life story of a first-year sea ice ridge. Cold Regions Science and Technology, 23(3): 279-290.

Leppäranta, M. and Shirasawa, K., 2007. Influence of the ice-ocean heat flux on the ice thickness evolution in Saroma-ko lagoon, Hokkaido, Japan, Proceedings of the 16th

International Northern Research Basins Symposium and Workshop, 27 August-2 September, 2007, Petrozavodsk, Russia. Карельский научный центр РАН, pp. 83-88.

Sharqawy, M.H., Lienhard, J.H. and Zubair, S.M., 2010. Thermophysical properties of seawater: a review of existing correlations and data. Desalination and Water Treatment, 16(1-3): 354-380.

Shirasawa, K., Ingram, R.G. and Hudier, E.J.-J., 1997. Oceanic heat fluxes under thin sea ice in Saroma-ko Lagoon, Hokkaido, Japan. Journal of marine systems, 11(1): 9-19.

Shirasawa, K., Leppäranta, M., Kawamura, T., Ishikawa, M. and Takatsuka, T., 2006. Measurements and modelling of the water: ice heat flux in natural waters, Proceedings of the 18th IAHR International Symposium on Ice. IAHR, pp. 85-91.

Timco, G., Croasdale, K. and Wright, B., 2000. An overview of first-year sea ice ridges.