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*Published in:*  
Cold Regions Science and Technology

*DOI:*  
[10.1016/j.coldregions.2020.102990](https://doi.org/10.1016/j.coldregions.2020.102990)

Published: 01/04/2020

*Document Version*  
Publisher's PDF, also known as Version of record

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*Please cite the original version:*  
Tikanmäki, M., & Sainio, P. (2020). Experiments on friction of dry and wet ice. *Cold Regions Science and Technology*, 172, Article 102990. <https://doi.org/10.1016/j.coldregions.2020.102990>

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# Experiments on friction of dry and wet ice

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## ARTICLE INFO

### Keywords:

Ice

Friction

Sliding

Wet ice

## ABSTRACT

Experiments on ice-on-ice friction both with and without water on the ice surface are presented. The experiments were conducted at  $-9.4^{\circ}\text{C}$  on dry ice and at  $-2.8^{\circ}\text{C}$  on both wet and dry ice. The sliding speed was varied between 6 and 105 mm/s. The effect of abrasion of ice surfaces was found to be an important phenomenon regarding the friction coefficient. Related to abrasion, the friction coefficient increased significantly in repetitive experiments especially at warm temperature. Adding water on the ice surface had only a minor effect on the friction coefficient at sliding speed above 10 mm/s. However, at lower speeds, the friction coefficient on wet ice was significantly higher than on dry ice.

## 1. Introduction

The friction of ice is an important phenomenon for example in car tire design and various winter sports. Friction between ice and ice is an important factor for example when estimating ice forces against ships and offshore structures (Tikanmäki et al., 2011). The friction of ice has been investigated both theoretically (e.g. Bäurle et al., 2007; Lozowski et al., 2013; Makkonen and Tikanmäki, 2014) and experimentally. Experimental research has been conducted on wide range of temperatures and speeds both using natural ice (e.g. Pritchard et al., 2012; Sukhorukov and Løset, 2013) and in laboratory. In laboratory studies, both rotational and linear devices (e.g. Oksanen and Keinonen, 1982; Kennedy et al., 2000; Marmo et al., 2005) have been used.

In field studies, the experimental setup might better represent the natural behavior of ice. However, in field studies, reaching comparable circumstances in terms of environmental variables and the homogeneity of ice is more difficult, and the reproducibility of results suffers from that fact. On laboratory-scale, it is more feasible to control environmental variables and produce repeatability in ice surfaces. When designing any experimental setup for ice friction it has to be considered that the layout of the experimental arrangement supports catching the phenomenon of interest. For example, with a rotational friction device one may warm up the ice sample to an unknown temperature thus making the interpretation of the results difficult (Makkonen and Tikanmäki, 2014).

In the interaction process between floating ice and an offshore structure, temperature at the bottom of the ice sheet is at the melting temperature of ice, and the sliding may happen both above and below

the waterline. In this study, the emphasis is on friction between two ice surfaces in warm temperatures, with and without additional water poured at the surface in contact. For simplicity, the terms wet and dry friction, respectively, are used in this paper even though melted water is assumed to be always present at the contact in the conditions of this study. The effect of salinity on ice-ice friction experiments has been shown to be minor (Kennedy et al., 2000) and thus, for simplicity, we concentrate in freshwater ice friction in this study.

Some studies with additional water on ice or with melting ice conducted both in a laboratory and at the field have been made before. Sukhorukov and Løset (2013) did field experiments on natural sea ice in the Barents Sea and in fjords of Spitsbergen. They did only limited amount of experiments on wet ice but their results indicate that the difference between dry and wet ice surfaces were minor. Jones et al. (1994) made laboratory experiments on melting ice on sliding speeds of 0.1–400 mm/s. In their experiments, the speed dependence between ice and other materials was not straightforward and varied between different materials but the lowest values of the friction coefficient were achieved at the lowest speeds and the highest values were achieved at the highest or intermediate speeds. This differs from the ice-ice friction coefficients measured around  $-10^{\circ}\text{C}$  summarized by Maeno and Arakawa (2004). In their summary, the friction coefficients on the same sliding speed interval were decreasing with increasing speed. Taking into account the discrepancy in these results more experiments are needed to build precise understanding of ice-ice friction on wet ice and at temperatures close to the melting point of ice.

In following, experimental setup and results of the ice-ice friction experiments performed at  $-2.8^{\circ}\text{C}$  and  $-9.4^{\circ}\text{C}$  are presented. At

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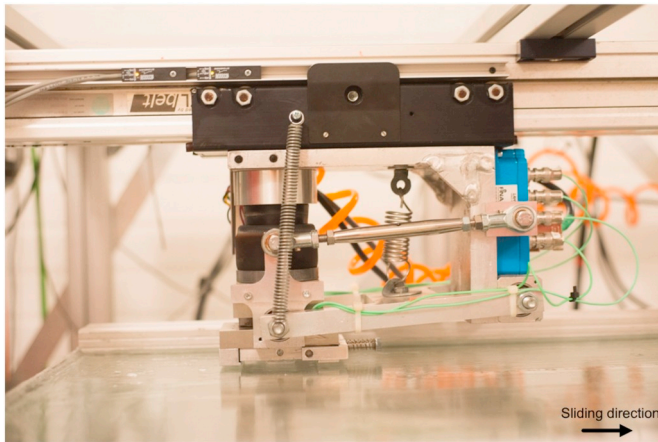


Fig. 1. Overview of the friction testing device MMR. An ice surface was frozen over a glass plate and smaller ice sample was attached to an aluminum holder and slid linearly over the larger ice surface.

–2.8 °C, the experiments were performed both on dry and wet ice.

## 2. Experimental setup

The experiments were performed on a mini-μ-road (MMR) in the Aalto University. MMR is shown in Fig. 1. MMR consists of an ice surface where a sample is slid linearly. The linear motion of the device is important to notice here since in rotational devices frictional heating of ice might be present and cause misinterpretations as discussed above (Makkonen and Tikanmäki, 2014). MMR is located in a cold room with thick brick and concrete structures making the temperature control stable. Details of MMR can be found in Rantonen et al. (2012).

The ice for the experiments was produced as follows. First, two identical ice surfaces of a depth of about 4 mm and a size of 0.5 m × 1 m were frozen by pouring small amounts of purified water that were at 0 °C over glass plates at –9.4 °C. The poured water was spread with a window cleaning spatula until it froze. After this, ice was allowed to stabilize to the air temperature before more water was poured. One ice surface was used as a base for sliding, and the other was used for cutting with a warm blunt steel plate the ice slider samples to a size of 2 cm × 3 cm. After cutting, the ice slider samples were frozen to an aluminum holder as shown in Fig. 2. The ice sample in aluminum holder was then flattened out by pressing warm steel plate against it in miniature drill press in a cold chamber. The importance of this was to ensure flatness and parallelism of moving ice sample and stationary ice plate. This ice making procedure produces granular ice with a grain size of 1–2 mm as shown in Fig. 3 where ice is shown

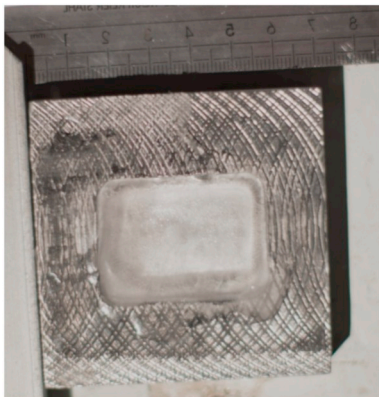


Fig. 2. Ice slider sample frozen onto an aluminum holder. The size of the samples was 3 cm × 2 cm.

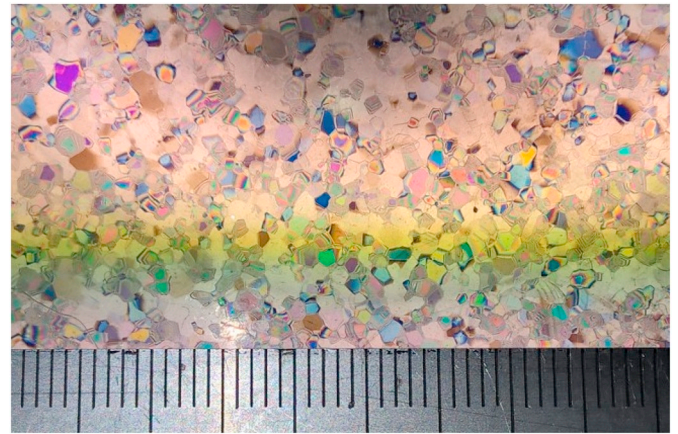


Fig. 3. Ice pictured through polarizing sheets. The grain size is 1–2 mm. The interval between the small ticks at the benchmark is 1 mm.

through polarizing sheets.

At the end of the first day of experiments, the ice sliding surface was regenerated by pouring few water layers on the surface. This water was again kept moving with a window cleaning spatula until it froze. After the second day or when the base ice was used with additional water on it, it was not regenerated anymore but another base ice was used at the next day.

The tests were performed at two temperatures, –2.8 °C and –9.4 °C, with a speed ranging from 6 to 105 mm/s. Two normal forces were applied. The higher normal force was on average 467 N (standard deviation 6 N) and the lower normal force was 280 N on average (standard deviation 3 N).

The tests were performed by sliding the ice slider sample over the larger ice surface. The sliding distance varied from 300 to 400 mm depending on the sliding speed. With sliding speeds less than 10 mm/s and with tests on wet ice, the sliding distance was 300 mm. In other tests, the sliding distance of 400 mm was used. The shorter sliding distance was used to limit the duration of the experiments and to ensure the endurance of the samples. When a new slider sample was taken, also a fresh track of the substrate ice was used. With each slider sample, the speed and the normal force were kept constant between runs. After every run, a break of 0.5–1 min was spent in order to allow the track to cool down to its original temperature. The temperature of the track was monitored with a thermographic camera. During the break between slides, small spalls of ice, that sometimes appeared, were removed by a soft plastic brush from the ice surface. For comparison, two test series were performed so that the ice surface was cleaned with a microfiber cloth after every run in order to smooth potentially existing crumbs of ice from the contact.

During the tests, the normal force  $F_N$  and the tangential force  $F_\mu$  were measured at every 0.2 mm step of sliding. The actual friction coefficient was calculated as the mean value of the fraction of these forces as  $\mu = \overline{F_\mu / F_N}$ . At the beginning and end of each slide, the slider accelerated and decelerated respectively. To ensure that only the part of the signal where the speed had stabilized at the desired value was taken into account, 12 mm of the beginning of the slide were neglected when calculating the coefficient of friction. This was found to be a safe limit for all the speeds to neglect the part of the signal where the slider was accelerating. At the end of the slide on dry ice, the part where the microscope camera was used was neglected in calculation of the friction coefficient to ensure that camera has no effect to the final results. This corresponds to the last 100 mm of the sliding track of length of 400 mm.

Dry ice experiments were run on a plain ice surface. Wet ice experiments were done so that about 1 dl of water that was at a temperature of 0 °C was poured on a plain ice surface. Water was poured before a new slider-surface pair was used, and the tests were

repeated without a break between subsequent runs. Water was kept moving with a rubber spatula to prevent the entire water film from freezing, and new water was poured on the surface when needed.

The evolution of the sliding surface was monitored by taking videos and photos below and above the glass plate with a standard camera, and photos of the sliding track were taken with a microscope camera. The microscope camera was not used to take photos of wet ice.

### 3. Theory

The results from the first runs are compared to the predictions of the model presented by [Makkonen and Tikanmäki \(2014\)](#). The model presents friction coefficient between two ice surfaces at the temperatures and velocities used here as

$$\mu = \frac{1}{\sqrt{a}H} \left( \frac{\Delta T \sqrt{k c \rho}}{\sqrt{2v}} + \sqrt{\frac{1}{2}(\Delta T)^2 k c \rho + C \eta v L \rho_w} \right) \quad (1)$$

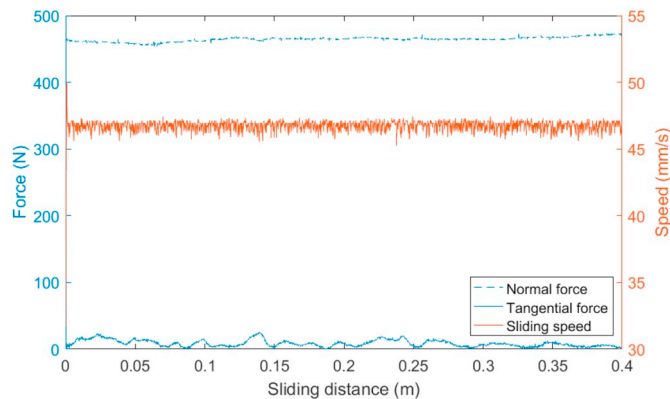
where  $a$  is the width of the contact,  $\Delta T$  the difference between the melting temperature of ice and the original temperature,  $k$  the thermal conductivity of ice,  $c$  the specific thermal capacity of ice,  $\rho$  the density of ice,  $C$  an iteratively determined factor describing the proportion of water not being squeezed out of the contact interface,  $\eta$  the viscosity of water,  $L$  the latent heat of melting of ice, and  $\rho_w$  the density of water. The contact width  $a$  is supposed to equal to 1 mm.

### 4. Results

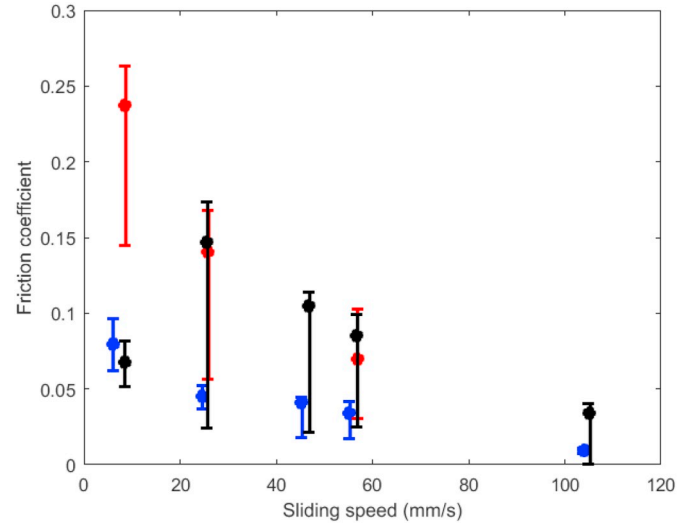
An example of the normal and tangential forces and sliding speed signals as a function of the sliding distance on dry friction case are shown in [Fig. 4](#). In this case, the temperature was  $-2.8^\circ\text{C}$  and the average sliding speed was 47 mm/s.

In [Fig. 5](#), measured ice-ice friction coefficients are presented as a function of sliding speed. Dots show mean values and bars show the range. Blue dots are for friction coefficients of dry ice measured at  $-9.4^\circ\text{C}$ , black dots for friction coefficients of dry ice at  $-2.8^\circ\text{C}$ , and red dots friction coefficients of wet ice at  $-2.8^\circ\text{C}$ . It can be seen that experiments conducted at  $-2.8^\circ\text{C}$  have large variation compared to the values achieved at  $-9.4^\circ\text{C}$ . In addition, the friction coefficient seems to lower with increasing sliding speed except the lowest speeds on dry ice at  $-2.8^\circ\text{C}$ .

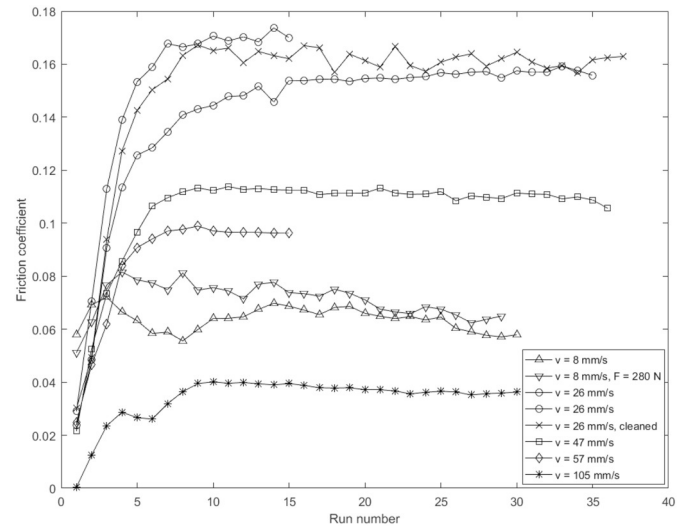
Another view to the results is achieved by plotting the ice-ice friction coefficients measured at  $-2.8^\circ\text{C}$  as a function of run number in [Fig. 6](#). The first run was performed with a new slider on an intact ice surface, and the subsequent runs with the same slider-surface pair at 0.5–1 min intervals. The normal force was on average 467 N if not otherwise stated. One series of tests at a speed of 26 mm/s was



**Fig. 4.** Example of the normal and tangential forces and sliding speed signals as a function of the sliding distance on dry friction case. The temperature is  $-2.8^\circ\text{C}$  and the speed is on average 47 mm/s.



**Fig. 5.** Ice-ice friction coefficients as a function of the sliding speed. Dots show mean values and bars show range. The blue ones are measured on dry ice at  $-9.4^\circ\text{C}$ , the black ones at  $-2.8^\circ\text{C}$ , and the red ones at  $-2.8^\circ\text{C}$  on wet ice. The circles show the mean values and the error bars show the range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



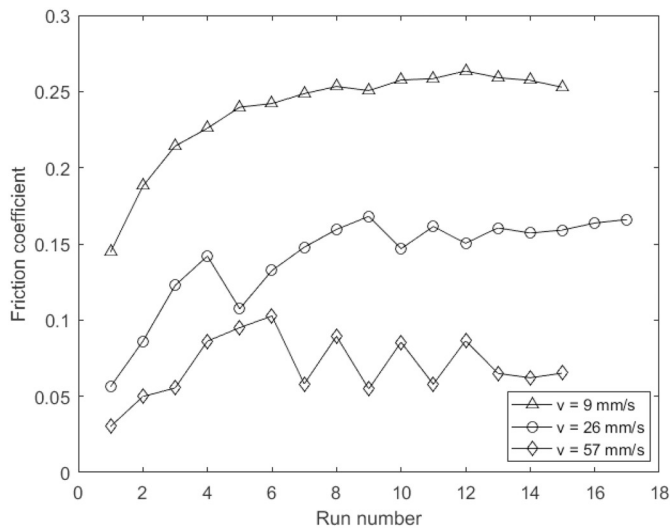
**Fig. 6.** Ice-ice friction coefficient on dry ice as a function of the run number at  $-2.8^\circ\text{C}$ . First run was performed with a new slider on an intact ice surface, and the subsequent runs with the same slider-surface pair with 0.5–1 min intervals. The normal force is 467 N if not otherwise stated. One series of tests at a speed of 26 mm/s was conducted so that after each slide the substrate ice surface is cleaned with microfiber clothing.

conducted so that after each slide the substrate ice surface was cleaned with microfiber clothing. It can be seen that the friction coefficient increases heavily at the first couple of runs especially at the intermediate sliding speeds. Cleaning the ice surface with microfiber clothing does not have an effect to the friction coefficient.

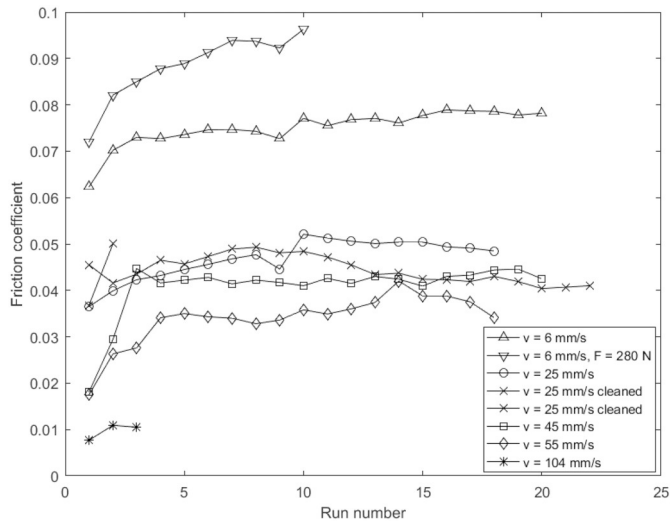
In [Fig. 7](#), the ice-ice friction coefficients are shown again at  $-2.8^\circ\text{C}$  but now on wet ice. No intervals are held between subsequent slides. The friction coefficient mostly increases as a function of the run number but not as remarkably as in the experiments on dry ice. The ice-ice friction coefficients measured at  $-9.4^\circ\text{C}$  on dry ice are shown in [Fig. 8](#). These results show less significant increase of friction coefficient as a function of the run number.

Friction coefficients of wet and dry ice at the first runs with each





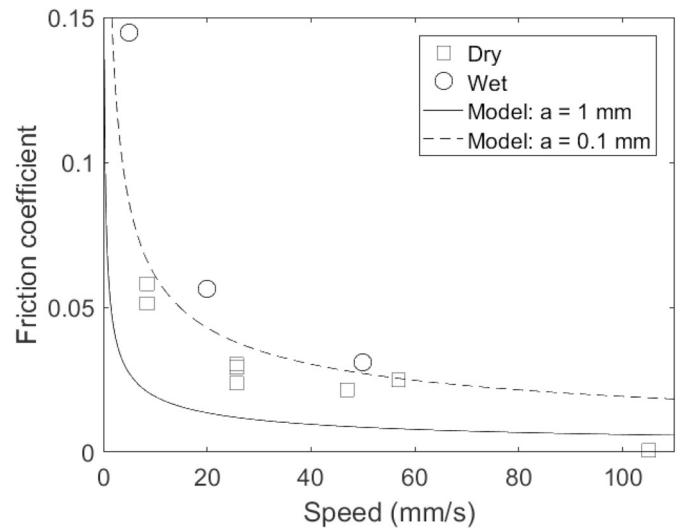
**Fig. 7.** Ice-ice friction coefficient as a function of the run number at  $-2.8^{\circ}\text{C}$  on wet ice. First run was performed with a new slider to intact ice surface, and the subsequent runs with the same slider-surface pair immediately after the previous run. The average normal force was 467 N.



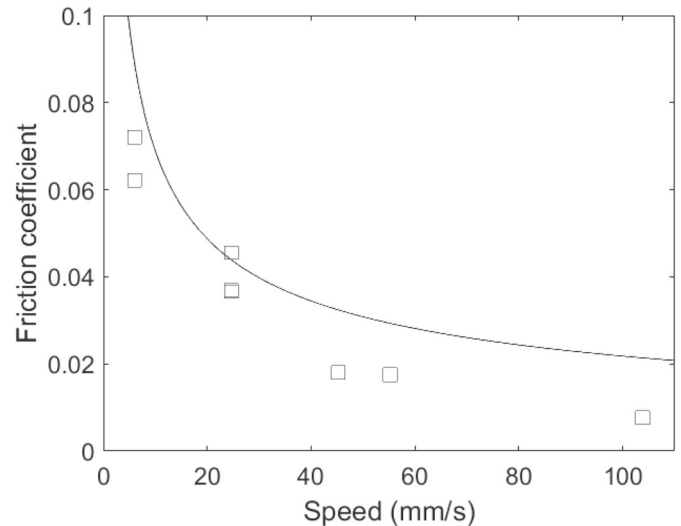
**Fig. 8.** Ice-ice friction coefficient as a function of the run number at  $-9.4^{\circ}\text{C}$ . First run is performed with a new slider to intact ice surface, and the subsequent runs are performed with the same slider-surface pair with 0.5–1 min intervals. The normal force was 467 N if not otherwise reported. Two series of tests at a speed of 26 mm/s was conducted so that after each slide the substrate ice surface is cleaned with microfiber clothing.

slider-surface pair at  $-2.8^{\circ}\text{C}$  and the corresponding prediction of the model with contact size values of 1 mm and 0.1 mm (Eq. (1)) by Makkonen and Tikanmäki (2014) are shown in Fig. 9. In Fig. 10, measurements from the first runs and the corresponding model results at  $-9.4^{\circ}\text{C}$  are shown.

To illustrate changes in the ice surface after runs, Fig. 11 shows, on the left, traces after the first run and on the right traces after the last run at a temperature of  $-2.8^{\circ}\text{C}$  with a speed of 47 mm/s, and a normal force of 467 N. The microscope camera was placed on the trace by hand so the figures in left and right are not from the exactly same place. Similarly, in Fig. 12, traces after first run are shown on the left and traces after the last run on the right at a temperature of  $-2.8^{\circ}\text{C}$ . In Fig. 13, the same traces are shown at a temperature of  $-9.4^{\circ}\text{C}$  with a speed of 55 mm/s, and a normal force of 467 N. The width of the photos is 7 mm and the height is 5 mm. The slider has moved from left to right.



**Fig. 9.** Ice-ice friction coefficients of the first runs at  $-2.8^{\circ}\text{C}$  on wet and dry ice. The solid curve is the theoretically modelled ice-ice friction coefficient curve from Eq. (1) with the original value of  $a = 1$  mm and the dashed curve is the same with  $a = 0.1$  mm.

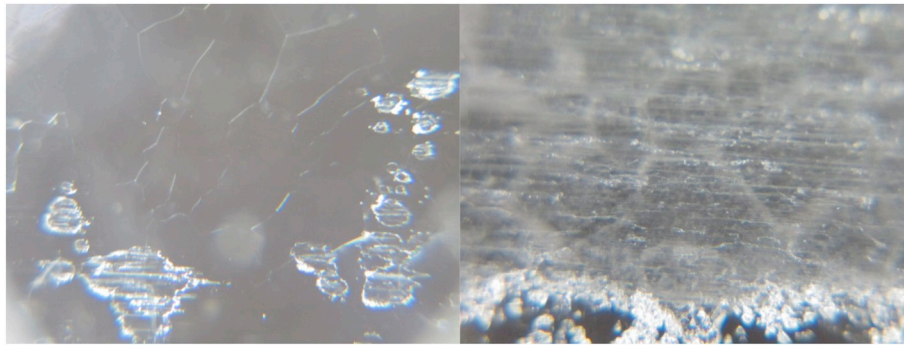


**Fig. 10.** Ice-ice friction coefficients of the first runs at  $-9.4^{\circ}\text{C}$ . The curve is the theoretically modelled ice-ice friction coefficient curve from Eq. (1) with the original value of  $a = 1$  mm.

Note that the tracks were 400 mm long and about 30 mm wide. The variability of traces left by the slider varied over the sliding track as can be seen from Fig. 14. Thus, a  $7\text{ mm} \times 5\text{ mm}$  footprint presented in Fig. 11, Fig. 12, and Fig. 13 does not present the whole area and the figures are thus to be taken as examples.

## 5. Discussion

The normal forces used in this study compared to many earlier studies are regarded to better represent the forces at the ice-ice sliding situation at the nature in the ice-structure interaction compared to the lower normal forces used in many earlier studies. However, higher loads caused fracturing of the ice samples. Due to this fact, the connection between the sliding ice sample and the aluminum holder needed to be designed to withstand the applied loading. This was done by carefully freezing the sample to the holder and taking extra care of parallelism between the surfaces after which the fracturing did not cause problems in the experiments.



**Fig. 11.** Traces after first run (left) and after 36 slides (right) at a temperature of  $-2.8^{\circ}\text{C}$ , at a speed of 47 mm/s, and a normal force of 470 N. The width of the photos is 7 mm and the height is 5 mm. The slider has moved from left to right. Border-like sharp lines are ice crystal boundaries.

Kennedy et al. (2000) made ice-ice friction tests with a linear test setup. At both temperatures, their friction coefficients are of the same magnitude than the values achieved here at the first runs on dry ice. Also, the measurements carried out here at the  $-9.4^{\circ}\text{C}$  show values of same magnitude to those measured in other experimental studies, as summarized by Maeno and Arakawa (2004). The similarity in the results in the first runs compared to the earlier studies suggests that the results are comparable. What makes the present experiments interesting is what happens in later runs on dry ice and when water is added on the sliding surface.

A significant observation in these tests was that, at a temperature of  $-2.8^{\circ}\text{C}$ , the friction coefficient increased significantly during the first couple of slides as a function of the run number, stabilizing only in later runs. At  $-9.4^{\circ}\text{C}$ , the friction coefficient most often increased as a function of the run number, but less significantly than at  $-2.8^{\circ}\text{C}$ . This phenomenon is different from what has been found in previous studies on ice-ice (Sukhorukov and Løset, 2013), ice-rubber (Rantonen et al., 2012), and ice-wood friction (Makkonen et al., 2016), where repetition of slides on the same track caused the friction coefficient to decrease.

The speed dependence of the ice-ice friction coefficient of wet ice was found to be similar to the one of dry ice except the lowest speeds, as can be seen in Fig. 5. When the sliding speed was 6–9 mm/s the friction coefficient of wet ice is significantly higher than the one without. Sukhorukov and Løset (2013) found out that the presence of sea water in the sliding interface has very little effect on the friction by sliding ice blocks on a natural sea ice submerged in sea water. On the contrary, Jones et al. (1994), found out that speed dependences between ice and other materials are found to be entirely different when measuring friction of melting ice. The conclusions from this study are thus closer to the conclusions by Sukhorukov and Løset (2013).

In Fig. 7, a zigzag pattern can be seen in the results with the highest speed. This is because water was not added on the surface and moved with a spatula for every run at the highest speed, as it was assumed that

quicker performing of the tests on wet ice would be sufficient for stability between runs.

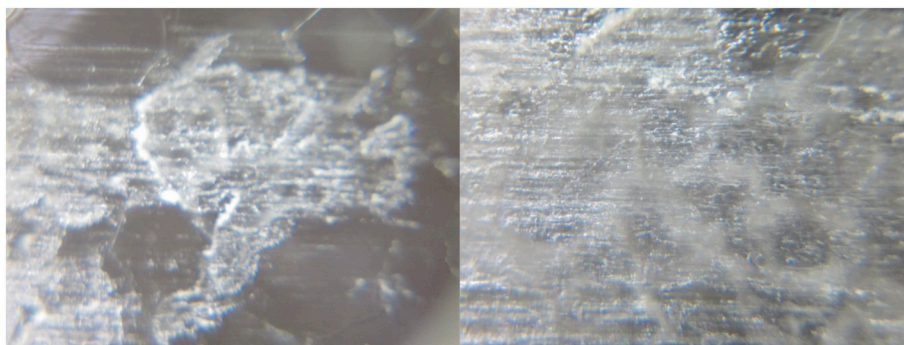
Additional water squeezed out of the square-shaped contact zone can be calculated according to the equation

$$\frac{1}{h^2(t)} - \frac{1}{h^2(0)} = \frac{2t\sigma}{0.421a^2\eta} \quad (2)$$

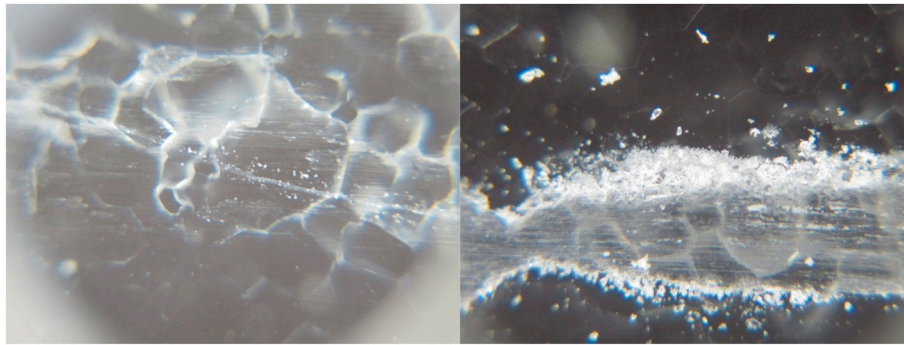
where  $h(t)$  is the thickness of the water layer as a function of time  $t$ , and  $\sigma$  is the perpendicular stress in the contact (Booser, 1983). Here,  $\sigma = H$ . At the beginning of the slide, the slider stayed at the same spot for 1.5 s. During this time, the additional water layer has time to squeeze out from the contact of assumed size 1 mm and reach the value of 3 nm according to the Eq. (2) if the original water layer is expected to be 1–2 mm. If the real contact size is smaller, the additional water layer becomes even thinner. This explains why the additional water does not have a clear effect at higher velocities at which the water layer thickness caused by the frictional heating increases as a function of the sliding velocity on dry ice. In the sliding phase, the slider is pushing water to the direction of the motion but the order of the magnitude of the drag force is negligible compared to the friction force.

The experiments on dry and wet ice surface were performed at an air temperature of  $-2.8^{\circ}\text{C}$ . However, pouring additional water of temperature of  $0^{\circ}\text{C}$  on the ice surface increased also the temperature of ice to  $0^{\circ}\text{C}$ . Thus, these experiments were not performed exactly at the same temperature of ice. The experiments were done immediately after each other on wet ice. At the speed 9 mm/s, it takes 33 s to one run, and at 57 mm/s, it takes 5 s to one run. Thus, at a lower speed ice has more time to absorb heat from the poured water and get softer. This tends to increase the friction coefficient thermodynamically (see, Eq. (1)) and mechanically by abrasion. This is thought to be the reason for higher friction coefficient values at the lowest speed on wet ice compared to the dry ice.

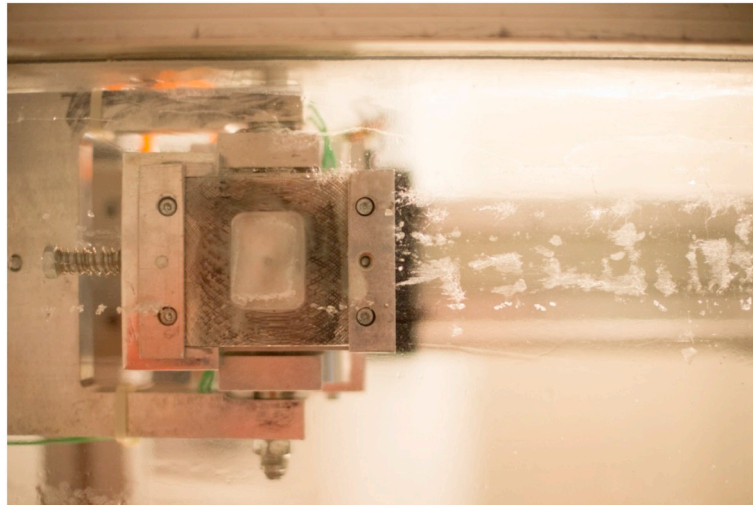
According to the photographic evidence, during the tests, both slider ice and substrate ice eroded. Some small ice fragments eroded



**Fig. 12.** Traces after first run (left) and after 30 slides (right) at a temperature of  $-2.8^{\circ}\text{C}$ , at a speed of 8 mm/s, and a normal force of 470 N. The width of the photos is 7 mm and the height is 5 mm. The slider has moved from left to right. Border-like sharp lines are ice crystal boundaries.



**Fig. 13.** Traces after first run (left) and after 18 slides (right) at a temperature of  $-9.4^{\circ}\text{C}$ , at a speed of 55 mm/s, and a normal force of 470 N. The width of the photos is 7 mm and the height is 5 mm. The slider has moved from left to right. Border-like sharp lines are ice crystal boundaries.



**Fig. 14.** View below the ice surface after many runs with high force. Eroding fragments at the sides and leaving edges of the slider and evolution of the frictional track on the ice surface can be seen. The slider is moving from right to left.

from the edge of the slider during the tests on dry ice. The tests with a certain slider and surface were stopped when enough runs were performed or a significant proportion of the sliding area was eroded. The evolution of the surface and the slider were monitored below and above the ice surface. After the tests, some waviness parallel to the direction of the motion could be felt on substrate ice. Fig. 14 shows a view below the friction table after several runs at a temperature of  $-9.4^{\circ}\text{C}$ . Eroding fragments at the edge of the slider and evolution of the frictional track can be seen.

As can be seen from Fig. 6, the ice-ice friction coefficient on dry ice at  $-2.8^{\circ}\text{C}$  increases at first couple of runs and then stabilizes. The friction coefficient at the first runs can be modelled when the contact size is taken as 0.1 mm as shown in Fig. 9. The stabilized value can be modelled quite well, except of the lowest speeds, with the ice friction model by Makkonen and Tikanmäki (2014) if the contact size is taken as 0.008 mm. This suggests that the sliding interface is changing rapidly during the couple of first slides changes on the interface can also be seen from the microscope photos shown from Fig. 11 to Fig. 13.

To find out whether there were small fragments of ice at the sliding surface effecting the friction coefficient, two experiments with a sliding speed of 20 mm/s were performed both at  $-2.8^{\circ}\text{C}$  and  $-9.4^{\circ}\text{C}$ . First, the experiments were carried out without touching the substrate ice in between different runs. Only larger spalls of ice, if they existed, were removed with very soft brushing. At the second experiment, the same parameters were used with a new slider-substrate ice pair. Now after every run, substrate ice was cleaned gently with a microfiber cloth. The slider was not cleaned. The pair of experiments gave values close to

each other at both temperatures as can be seen from Fig. 6 and Fig. 8. This suggests that no loose ice particles were present at the surface at the later runs. In addition, in linear sliding, the slider would plough all loose particles in front of it if such particles existed. Thus, it can be concluded that the changes during the first runs are rather happening at the surface of ice.

At  $-9.4^{\circ}\text{C}$ , the level of friction coefficient increases less significantly between the runs than at  $-2.8^{\circ}\text{C}$  as can be seen by comparing Fig. 6 and Fig. 8. Ice at  $-9.4^{\circ}\text{C}$  is significantly harder than at  $-2.8^{\circ}\text{C}$ , and thus changes at the contact interface might be smaller between the slides. In contrary to present results, Sukhorukov and Løset (2013) found out that the increasing run number decreases the friction coefficient between ice and ice. Their experiments with increasing run number were performed in unpolished natural sea ice. The size of their ice blocks were larger than the ones used here being approximately 30 cm  $\times$  30 cm. Their normal force was smaller being about 200 N. In our experiments surfaces of ice were very smooth, sample was 1/150 as area and the normal force was higher i.e. nominal surface pressure was much higher. The term smooth has to be understood here as a local property of ice. In larger scale, say 50–200 mm, there is small variation in evenness of ice. In addition, when the slider travels over ice it may compact crushed ice in small amounts locally. This might have caused the shaping of the surface of the ice and thus cause the increase in the friction coefficients in the present experiments. This is supported by the observation that this phenomenon is more significant at the higher temperature were the hardness of ice is lower, and thus ice is more easily shaped.



At speeds of 6–9 mm/s, experiments were performed with normal forces of 280 and 467 N. At both temperatures, the friction coefficient with a normal force of 280 N was higher than with 467 N. At  $-2.8^{\circ}\text{C}$ , the difference was smaller than at  $-9.4^{\circ}\text{C}$ . The theoretical model (Makkonen and Tikanmäki, 2014) suggests that the normal force does not have a significant effect in ice-ice friction. Because of the large normal forces used in this experiments also shapening of the ice is present and the normal force might have an effect. In order to make clear statements about the effect of this large normal forces, more experiments on different load levels are needed.

A thermographic camera was used to detect whether the sliding interface was warmed during the slides. The results show that the temperature of the substrate ice cooled to its initial temperature between repetitive slides. The temperature of the sliding ice sample could only be measured after the last run when it was about two degrees warmer than the initial cold chamber temperature.

A microscope camera was used to monitor the evolution of the sliding track between runs. From the microscope photos in Fig. 11, Fig. 12, and Fig. 13, it could also be seen that there were traces of varying sizes left behind. From these photos, it was evident that the apparent sliding area was not completely in contact which supports the use of contact size smaller than the apparent contact size in the friction model (Eq.(1)). The conclusion that the softer ice at  $-2.8^{\circ}\text{C}$  has eroded more than the harder ice at  $-9.4^{\circ}\text{C}$  is supported by these figures.

Left sides of the Fig. 11, Fig. 12, and Fig. 13 as well as other photos taken with a microscope camera support the idea that not the whole area of the slider is in contact with ice at the first run. This supports the choice of the characteristic contact size  $a$  being less than the apparent slider width. The place of the contact is sometimes changing quickly when the slider is moving forward as can be seen from Fig. 11. The photos taken with a microscope camera also show that the characteristic contact size  $a$  in the friction model (Eq. (1)) is not a constant value but has to be taken as a mean value. It can be seen from the changes from the left to right sides of the Fig. 11, Fig. 12, and Fig. 13 that the nature of the contact has changed as a function of the run number that also supports the reasoning of changing contact as a reason for the increasing value of the friction coefficient.

## 6. Conclusions

In this paper, ice-ice friction coefficients at temperatures of  $-2.8^{\circ}\text{C}$  and  $-9.4^{\circ}\text{C}$  were presented. At  $-2.8^{\circ}\text{C}$ , experiments were performed both on wet and dry ice surface. Successful performing of the tests demanded a well-designed testing apparatus MMR, and overcoming of specific problems arising from the low values of the ice-ice friction coefficient and ice fracture under a high normal force.

The effect of abrasion of ice surfaces was found to be an important phenomenon regarding the friction coefficient between ice and ice. A significant notion in these experiments was that the friction coefficient increased significantly in repetitive experiments in contradiction to earlier studies conducted with pairs of ice-ice, ice-rubber, and ice-wood where polishing of ice led to decrease of the friction coefficient.

The experiments performed on wet ice showed friction coefficients close to the ones measured on dry ice. However, at a low speed of

6–9 mm/s, friction coefficient of wet ice was significantly higher than on dry ice. The similarity of the values on dry and wet ice is probably caused by the additional water being squeezed out from the true contacts before the actual test starts, and that the water layer thickness caused by the frictional heating increases with increasing speed. The difference of the values at the lower velocity can be because repeating runs at lower speed and keeping the sliding distance same requires more time and thus the ice has more time to warm up from its original temperature of  $-2.8^{\circ}\text{C}$  to the temperature of the poured water being  $0^{\circ}\text{C}$ . This results in a warmer ice and a higher friction coefficient.

The results from this study give new knowledge from the evolution of the ice-ice friction in subsequent sliding runs and the friction coefficient of wet ice. Experiments on wet ice at the original ice temperature of  $0^{\circ}\text{C}$  would give more insight of the subject. However,  $0^{\circ}\text{C}$  being the melting temperature of ice makes such experiments extremely challenging if not impossible.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

The authors wish to thank Lasse Makkonen for the comments on the plans of the experiments and for comments on the manuscript, Kari Kolari for the comments on the manuscript and Toni Hekkala for the photographs 1, 2, and 14. This work was funded by the Academy of Finland, Grants no. 268829 and 297278.

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