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Modelling sea ice friction with a thermodynamic friction model

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The dynamic friction of ice can be estimated by thermodynamic models. The authors have developed a thermodynamic ice friction model, which is summarized in this paper. This model can be applied to dynamic friction between ice and some other material, and to ice–ice friction. The model has been successfully verified by laboratory experiments using freshwater ice. Here, we discuss the applicability of this model to sea ice friction and use it in explaining ice friction measurements presented in the literature for saline ice. We identify the discrepancies and develop the model accordingly. The improved model can be used in estimating friction on a vessel navigating in ice and in modelling sea ice dynamics and ice crushing processes.

1. Introduction

The friction of ice is a fundamental phenomenon in numerous applications, including tire-pavement friction, falling accidents, and winter sports. In this paper, the emphasis is on the friction of sea ice sliding on sea ice, which is important in applications such as modelling the ice load against offshore structures, the dynamics of ice floes and the performance of ships operating in ice-covered waters. The ice friction model used for simulating the ice loads on offshore structures significantly affects the simulated load levels (Tikanmäki et al., 2011).

The first quantitative model for the friction of ice was derived by Oksanen and Keinonen (1982). This model was based on the thermodynamic equilibrium and was further developed by Makkonen and Tikanmäki (2014). The model has been successfully verified against laboratory measurements with freshwater ice and it can be used to estimate kinetic friction between freshwater ice and some other material or ice–ice friction. However, the effect of salinity has not been taken into account in the model.

Most friction experiments have been performed in a laboratory with freshwater ice (e.g. Marmo et al., 2005). However, some friction measurements have been conducted also with saline ice both in laboratory (Kennedy et al., 2000; Frederking and Barker, 2002) and in the field (Pritchard et al., 2012; Sukhorukov and Løset, 2013).

In this paper, the ice friction model developed by Makkonen and Tikanmäki (2014) is briefly summarized. The applicability of the model to sea ice friction is discussed. The significant differences between freshwater and sea ice friction are defined and the model is further developed accordingly. The model is used to explain the results of friction experiments conducted in laboratory (Kennedy et al., 2000; Frederking and Barker, 2002).

2. The friction model

The friction model is explained in detail by Makkonen and Tikanmäki (2014). Here, the theory is briefly introduced and the most relevant equations are presented. The friction theory concerns dynamic friction and consists of two parts: dry and wet friction. The contact is wet when frictional heat melts ice at the contact zone and lubricates the contact. When there is not enough frictional heat to melt the layer of ice the friction is assumed to be dry.

The dry friction occurs in the nanoscale contacts and the theory by Makkonen (2012) provides μ as

$$\mu = \frac{\gamma(1+\cos\theta)}{2dH_I} \qquad \textbf{[1]}$$

where γ is the surface energy of ice, θ is the equilibrium contact angle of sessile water drop on a material's surface, d is the characteristic nanoscale contact length and H_I is the indentation hardness of the softer one of the two materials. For ice-ice friction, the friction coefficient can be expressed as

$\mu = \frac{\gamma}{dH}$, **[2]**

where H is the hardness of ice.

The wet friction is thermodynamically controlled and the friction coefficient μ can be estimated by

$$\mu = \frac{1}{\sqrt{a}H_I}\left(\frac{1}{2\sqrt{2v}}\left(\Delta T_1\sqrt{k_1c_1\rho_1} + \Delta T_2\sqrt{k_2c_2\rho_2}\right) + \sqrt{\frac{1}{8}\left(\Delta T_1\sqrt{k_1c_1\rho_1} + \Delta T_2\sqrt{k_2c_2\rho_2}\right)^2 + \eta v L\rho}\right)$$ **[3]**

where a is the width of the contact, ΔT_1 the difference between the melting temperature of ice and the original temperature of ice, , ΔT_2 the difference between the melting temperature of ice and the original temperature of the slider, k_1 the thermal conductivity of ice, c_1 the specific thermal capacity of ice, ρ_1 the density of ice, η is viscosity of water, L is the latent heat of melting of ice and ρ is the density of water. At the wet friction, the contact width a is supposed to equal 1 mm.

In the model, the hardness of ice H is parameterized as

$H(T) = C_1T + C_2$ **[4]**

where $C_1 = -5.08$ and $C_2 = 15.19$. Here, H is in MPa and the temperature of the ice T in °C. The dependence of the equilibrium melting temperature of pure ice T_f on hardness of the softer material H_I is taken as

$T_f = -7.43 \times 10^{-2} H_I$. **[5]**

Also, squeeze-out of water at the contact is taken account with iterative procedure which is explained in detail by Makkonen and Tikanmäki (2014).

3. The effect of salinity

The friction model has previously been used to estimate friction coefficients of freshwater ice (Makkonen and Tikanmäki, 2014). Now, the effect of salinity is taken account. Firstly, the freezing temperature of saline ice differs from the one of freshwater ice. This changes the equilibrium temperature of the contact zone. The freezing temperature of the ice can be estimated by

$T_s = -54s - 600s^3$ **[6]**

where s is the salinity of ice in ppt (Makkonen, 1987). For a typical salinity of sea ice around 5 ppt, the freezing temperature equals to -0.27ºC.

Secondly, the hardness H of saline water might differ from the one of the freshwater ice. In the model, the hardness of freshwater ice is based on the measurements by Barnes and Tabor (1966). To our knowledge, the effect of salinity to the hardness of ice has not been investigated thoroughly. Hardness of level ice and consolidated layer has been measured in the Barents Sea and Van Mijen fjord in Svalbard (Høyland et al., 2004) showing lower values of H than in the laboratory tests with freshwater ice (Barnes and Tabor, 1966). However, the results were reported to vary depending on the person testing (Høyland et al., 2004). Due to the lack of consistent data on the hardness of saline ice, it is assumed in our model that the salinity does not affect ice hardness, and the parameterization of Makkonen and Tikanmäki (2014) is used. A supporting argument here is that the actual contact and its deformation occur at a scale smaller than the typical spacing of the brine pockets and grain boundaries.

The latent heat of melting, specific heat, and heat conductivity are parameterized in the model as given by Schwerdtfeger (1963). The mean density of saline ice is taken as 910 kg/m^3 (Timco and Weeks, 2010). Taking into account the ice salinity in these parameters affects the friction coefficient only slightly, except that at temperatures close to the melting point the specific heat of saline ice is so much higher than that of freshwater ice that the increase in the friction coefficient is noticeable.

The surface energy of freshwater ice is 73 $\mathrm{mJ\,m^{-2}}$ (Makkonen 1997). The surface energy of the sea ice is not known. In certain conditions, a salt layer can exist on a sea ice surface. Thus, a surface energy of the NaCl 114 $\mathrm{mJ\,m^{-2}}$ (Bahadur et al., 2007) sets an upper bound to the surface energy of the sea ice. It is assumed in the model that the effective surface energy of saline ice is the same as that of freshwater ice.

4. Results and comparisons with experiments

The friction of saline ice has been measured in laboratory (Kennedy et al., 2000; Frederking and Barker, 2002) and in field (Pritchard et al., 2012; Sukhorukov and Løset, 2013).

The laboratory measurements by Kennedy et al. (2000) were done at low sliding velocities and with both saline and freshwater ice. The measurements were conducted by linear tribometer which does not cause additional warming of the ice. Thus, the experiments provide an excellent verification data for the differences between friction models for saline and freshwater ice. However, the results of these experiments are for low sliding velocities only and do not indicate significant differences between the friction coefficients of saline and freshwater ice.

Laboratory experiments of friction of sea ice have been conducted on various construction materials by Frederking and Barker (2002). They also conducted tests with sea ice on sea ice.

The measurements conducted in the field (Pritchard et al., 2012; Sukhorukov and Løset, 2013) give much higher friction coefficients than those made in the laboratory (Kennedy et al., 2000). This might be due to the fact that in the field the environmental conditions are not easy to maintain and there might additional processes like ploughing involved due to a higher roughness of the ice surface.

5. Results

In Figures 1 to 4 some results of the model are presented together with corresponding experimental data. The model results agree reasonably well with the experimental data. However, at -40°C and low sliding speed, the model underestimates the friction coefficient. This is probably due to linearly extrapolating the ice hardness from warmer temperatures in the model, since actual data are missing.

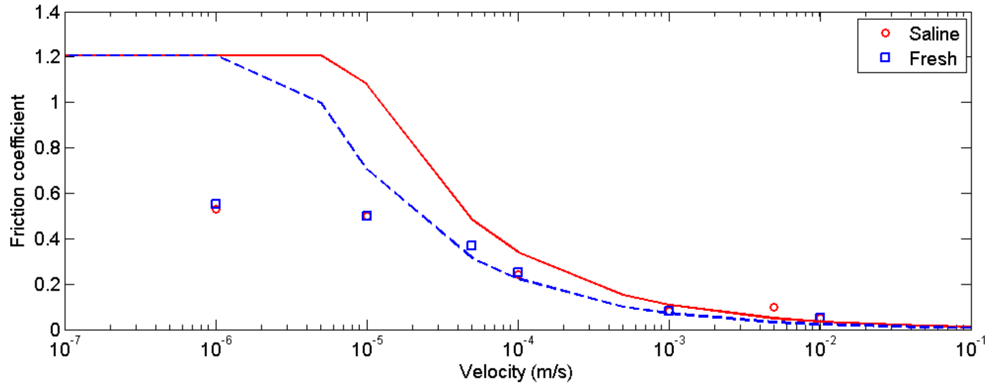

Figure 1. Comparison between saline and fresh water ice friction at temperature -3°C. The measurements are from the Kennedy et al. (2000).

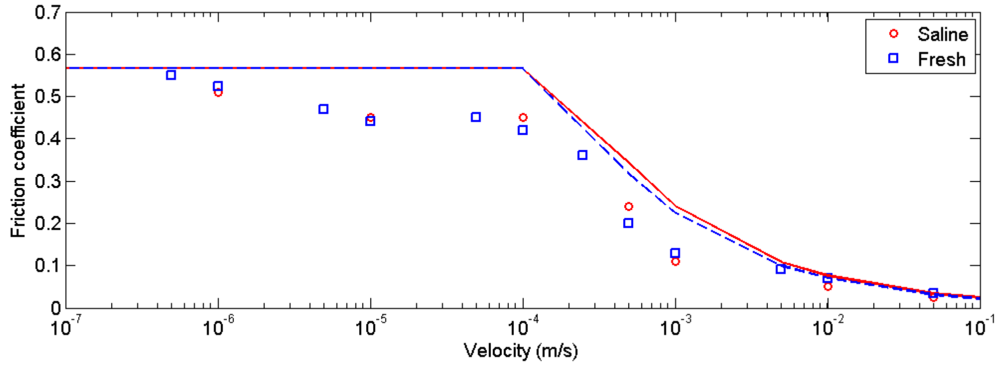

Figure 2. Comparison between saline and fresh water ice friction at temperature -10°C. The measurements are from the Kennedy et al. (2000).

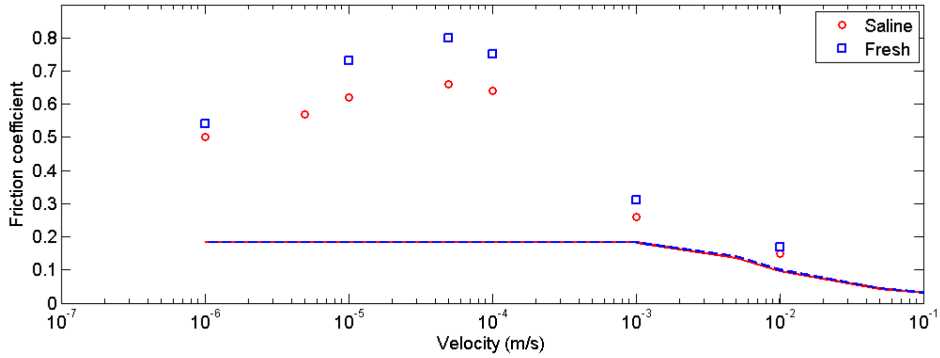

Figure 3. Comparison between saline and fresh water ice friction at temperature -40ºC. The measurements are from the Kennedy et al. (2000).

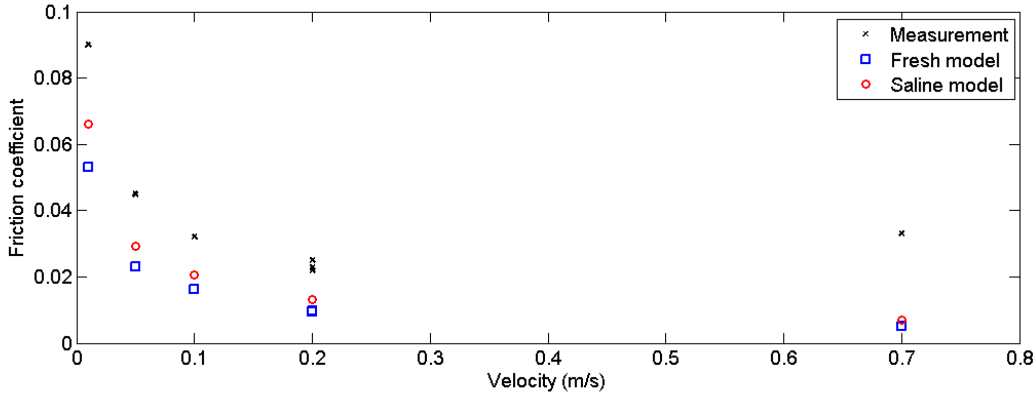

Figure 4. Comparison between measurements and the model. The temperatures of the individual points vary from -2ºC to -6ºC. The measurements are from the Frederking and Barker (2002).

6. Discussion and conclusions

The model results suggest that ice-ice friction does not change much because of salinity of ice. The measurements support this general conclusion at low sliding speed.

Limited number of experimental data of the friction of saline ice has been made, particularly at a high sliding speed. Especially, there is a lack of experiments where both freshwater and saline ice has been used. If different experimental setups are compared the difference due to setups might be larger than the difference due to freshwater and saline ice (Makkonen and Tikanmäki 2014).

The hardness of saline ice remains still an open question. The effect of hardness in the model is large and the model could be made more accurate with proper hardness values. This aspect of the modeling should be studied more, particularly as relates to the hardness at very cold temperatures and close to the melting point.

Acknowledgments

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