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FRICTION MODELLING IN ICE CRUSHING SIMULATION

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ABSTRACT

The objective of this paper is to present an ice friction model and implement it to ice crushing simulation. This friction model is based on thermodynamic equilibrium and enables determining the friction coefficient between ice and ice or some other material as a function of the sliding velocity and temperature. The hardness of ice is found to be an important property in the friction mechanism. Comparison of modelled friction coefficients and experimental results is made. In this paper the friction model is implemented to the modelling of the crushing of ice against off-shore structures and ships.

INTRODUCTION

Friction of ice affects performance of ships operating in sea or lake ice and stationary structures in moving ice fields. Evidently, the related ice crushing phenomena involve not only structure-ice friction but also friction between ice particles in different scales. In previous models friction of ice has been considered simply by assuming a certain fixed friction coefficient. The purpose of this work is to present a detailed ice friction model and implement it to the ice crushing simulations. The friction model is verified and adjusted to give reliable friction coefficients between fresh water ice and other materials with different sliding speeds and temperatures.

FRICTION MODEL

It has been shown that, due to frictional heating, a water layer forms between ice and a slider at typical temperatures (Bowden and Hughes, 1939, Hobbs, 1974). This layer is thicker than the quasi-liquid layer that exists on an equilibrium ice-vapour interface (Makkonen, 1997). Therefore, we can assume that at temperatures not far from 0°C frictional sliding force is caused by viscous shear in the water layer, i.e.

$$F_\mu = \tau A = \eta_0 \frac{dv}{dy} A = \eta_0 \frac{v}{d} A, \qquad (1)$$

where τ is shear stress, A contact area, η_0 viscosity of water, v sliding velocity and d thickness of the water layer. The coefficient of friction is

$$\mu = \frac{F_\mu}{F_N}, \qquad (2)$$

where F_N is the normal force.

It has been also noted that coefficient of friction changes as a function of temperature and sliding speed (Bowden and Hughes, 1939, Hobbs, 1974). This supports the use of the thermodynamic friction model presented by Oksanen and Keinonen (1982). The apparent contact surface is assumed to consist of a number of real contacts. The schematic contact surface is shown in Figure 1. Noting, that frictional heating is conducted to the ice and the slider and spent in melting of ice, and eliminating the thickness of the water layer d, the friction coefficient μ can be determined by equations (1) and (2). The friction coefficient μ for sliding on ice is, therefore

$$\mu = \frac{1}{\sqrt{a}H}\left[\frac{1}{2}\sqrt{\frac{1}{2v}\left(\Delta T_1\sqrt{\lambda_1 c_1 \rho_1} + \Delta T_2\sqrt{\lambda_2 c_2 \rho_2}\right)} + \sqrt{\frac{1}{8v}\left(\Delta T_1\sqrt{\lambda_1 c_1 \rho_1} + \Delta T_2\sqrt{\lambda_2 c_2 \rho_2}\right)^2 + \eta_0 v h \rho_0}\right], \tag{3}$$

where a is contact size, H is hardness of the softer material, v is sliding velocity, ΔT is temperature difference between melting point of ice and surface, λ is heat conductivity, c is specific heat capacity, ρ is density, η_0 is viscosity of water, h is latent heat of melting for ice and ρ_0 is thickness of water. The subscript 1 refers to ice and 2 to the slider material. Here the equation of friction coefficient is slightly modified from the original model by Oksanen and Keinonen (1982) by noting that

$$H = \frac{F_N}{A} = \frac{F_N}{na^2}, \tag{4}$$

where n is the number of contacts. Material constants used in this paper are shown in Table 1.

Table 1. Material constants used in this paper.

	Ice	Water	Steel	Concrete
λ (W m^{-1}K^{-1})	2.2		14	1.7
c (J kg^{-1}K^{-1})	2090		450	900
ρ(kg m^{-3})	916	1000	8000	2400
η_0 (kg m^{-1} s^{-1})		$1.76 \cdot 10^{-3}$		
h (kJ kg^{-1})	330			

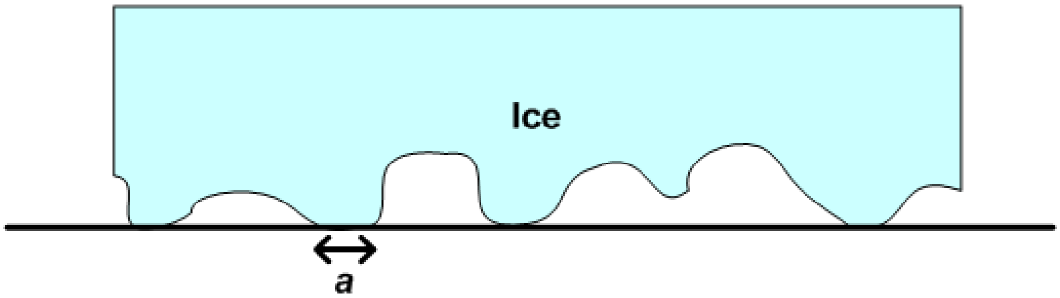

Figure 1. Schematic contact surface. Characteristic length of contacts is a.

Equation (4) is based on a simple contact mechanics model in which the real contact pressure equals the indentation hardness of the softer material. In the applications considered here, the softer material is ice. Therefore, hardness of ice is required for the friction. Since the contact size a is smaller than the typical size of grains of ice, the hardness of single ice grain is used here. Measurements of ice grain hardness at different temperatures have been made by Butkovich (1958). He presented the resulting hardness in the Brinell scale. After the converting to MPa his results for the 12 s contact time can be presented as

$$H(T) = C_1T^2 + C_2T + C_3, \tag{5}$$

where $C_1 = -0.0138$, $C_2 = -3.1448$ and $C_3 = 28.0753$. H is in MPa and T in °C. This result is shown in Figure 2.

The penetration depth of the indenter in the experiments by Butkovich (1958) is of the same order of magnitude as the ice layer that in this theory typically heated during a lifetime of a single contact. Therefore, it is assumed here that frictional heating of a contact affects its hardness. Assuming the temperature distribution to be linear in the vertical direction, the average temperature in the heated layer is

$$\bar{T} = \frac{T_1}{2}, \tag{6}$$

as shown in Figure 3. This temperature is used in the model in determining the ice hardness by eq. (5).

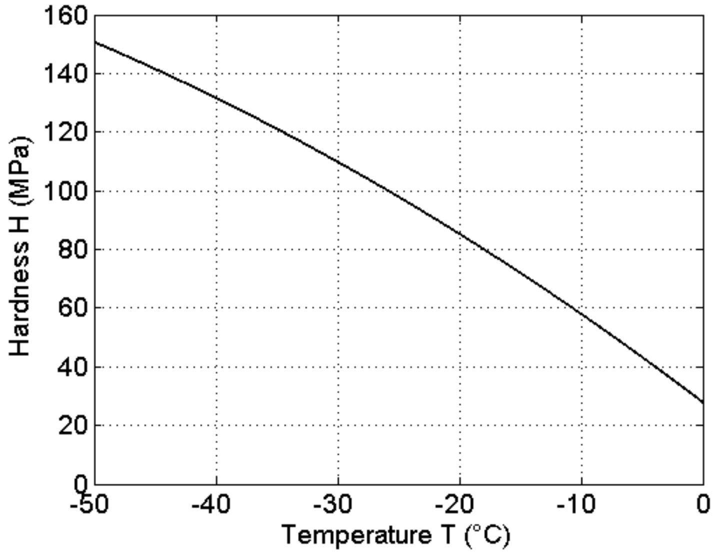

Figure 2. Hardness of single grain of ice as a function of temperature in the model (based on experimental data by Butkovich (1958)).

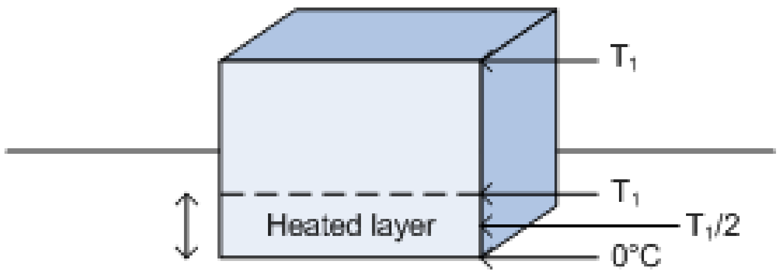

Figure 3. Heated layer of a single contact.

A further modification to the thermodynamic theory of Oksanen and Keinonen (1982) is made here in that the effect of the melting temperature of ice with contact pressure is added to the model. As noted above, the real pressure at a contact $P_c = \frac{F_N}{A}$ is assumed to correspond to the hardness of ice. The change in the melting temperature T_m depends on the pressure P_c as

$$\frac{dT_m}{dP_c} = -7.43 \cdot 10^{-8} \frac{\text{°C}}{\text{Pa}}. \qquad (7)$$

When using the model, the change in the melting point is taken account in the thermodynamics (eq. (3)). However, the hardness values are not changed due to this effect because it is assumed to exist already in the measured hardness.

VERIFICATION OF THE FRICTION MODEL

Verification of the theoretical friction model is surprisingly hard because most of the friction measurements of ice have been done so that same sliding surface is used repeatedly and, hence, the real effective surface temperature is unknown.

Here the friction model is compared with the friction measurements between ice and steel made by Marmo *et al.* (2005). They made 449 measurements of friction coefficient over a temperature range from -27 to -0.5°C and a velocity range from 0.008 to 0.37 m/s. They used a linear tribometer when sliding ice hemispheres on a steel substrate. Measurements where made in a chest freezer and before each experiment the steel sheet was wiped with long-fibre tissue to remove the surface frost. They plotted results from these experiments in temperature-velocity space and contoured the coefficient-of-friction data. Their results are shown in
Figure 4.

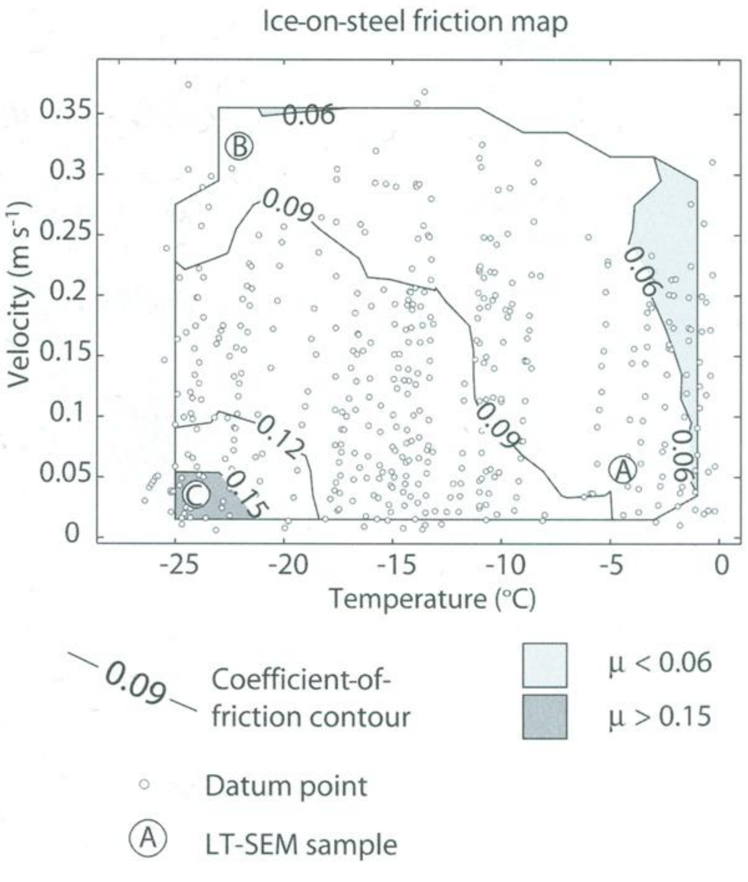

Figure 4. Experimental friction map from Marmo et al. (2005).

The friction coefficient between ice and steel were defined in the same temperature-velocity space according to the theory presented in this paper. Characteristic contact size a between ice and steel was approximated to be 1 mm. Material constants used in the calculations are shown in Table 1. These model results were plotted similarly to Figure 4 and are shown in

Figure 5 using same contour levels. It can be seen that the theory explains remarkably well the measurements by Marmo *et al.* (2005).

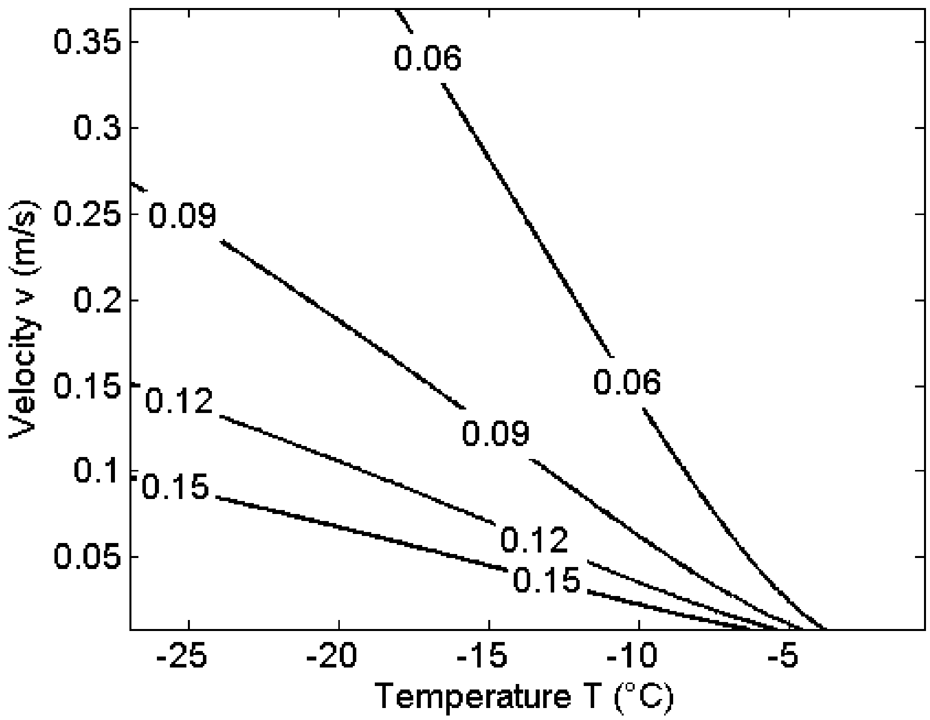

Figure 5. Friction map by the theoretical model presented here. The numbers give the friction coefficient for ice-on-steel friction.

These verifications are for fresh water ice only. However, extensive laboratory experiments by Kennedy *et al.* (2000) indicate that the ice-ice friction coefficient is almost independent of ice salinity at all temperatures in a wide range of sliding velocities.

FRICTION MODELLING IN ICE CRUSHING SIMULATION

Since the theoretical model presented here seems to fit well to the experimental data it is reasonable to use this model for defining the friction coefficients in ice crushing simulation rather than use for example a constant friction coefficient. It is relatively straightforward to use the friction model in the crushing model. The model was implemented to the ABAQUS/Explicit software as a user-defined general contact friction model (VFRICTION). ABAQUS/Explicit is commercial software used for finite element method modelling.

The effect of the friction model was investigated by a structure-ice model developed earlier at VTT. In the model the level ice sheet is moving against the rigid offshore structure at velocity of 0.1 m/s. The situation is illustrated Figure 6. In the crushing model thin connection elements are placed between the cubical ice elements. Connection elements behave like elastoplastic material having anisotropic, stress based failure criterion. These elements are removed after they are damaged and ice cubes are disconnected. In the simulation the characteristic contact size between surfaces was chosen to be 1 mm. Values of the material constants used in the analysis are shown in Table 1.

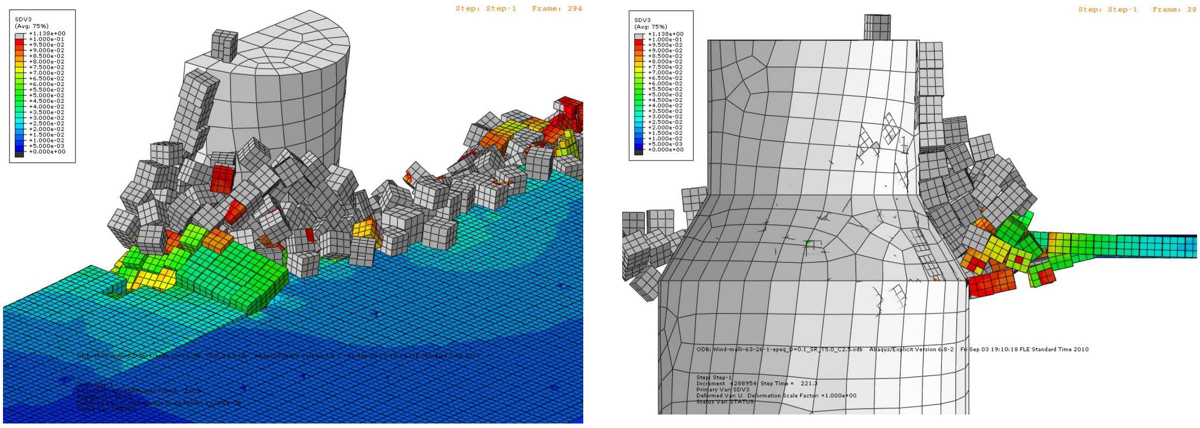

Figure 6. The structure-ice model. Ice is moving against the rigid offshore structure.

Crushing simulations were run in temperatures -3 and -10°C to investigate the effect of the friction modelling to the simulated force levels against the structure. Ice-concrete friction coefficient dependence on sliding velocity in temperatures -3 and -10°C according to the presented theory is shown in Figure 7. To highlight the importance of the friction in crushing the simulations were run also with a constant friction coefficient μ = 0.15 used previously in ice crushing models.

The time histories of the forces against the structure in the direction of the motion in different simulations are shown in Figure 8. The difference in the maximum resultant normal forces against the structure in the direction of the motion was 20% at temperatures -3 and -10°C. For comparison the maximum resultant forces at temperatures -3 and -10°C were 50-60% smaller than the force simulated with the constant friction coefficient μ = 0.15. This emphasizes the importance of proper friction modelling in crushing simulations.

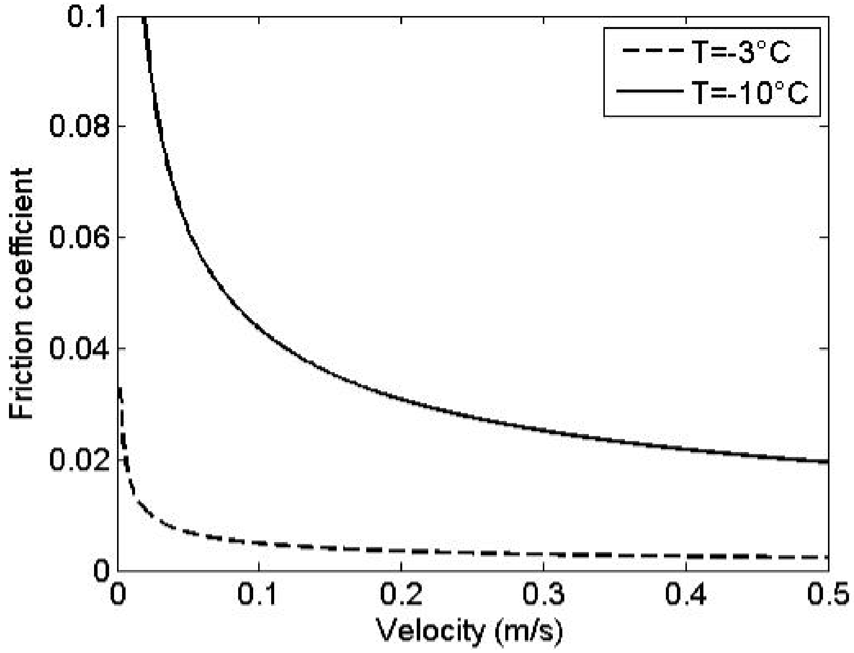

Figure 7. Ice-ice friction coefficient at temperatures -3 and -10°C vs. velocity based on the presented model.

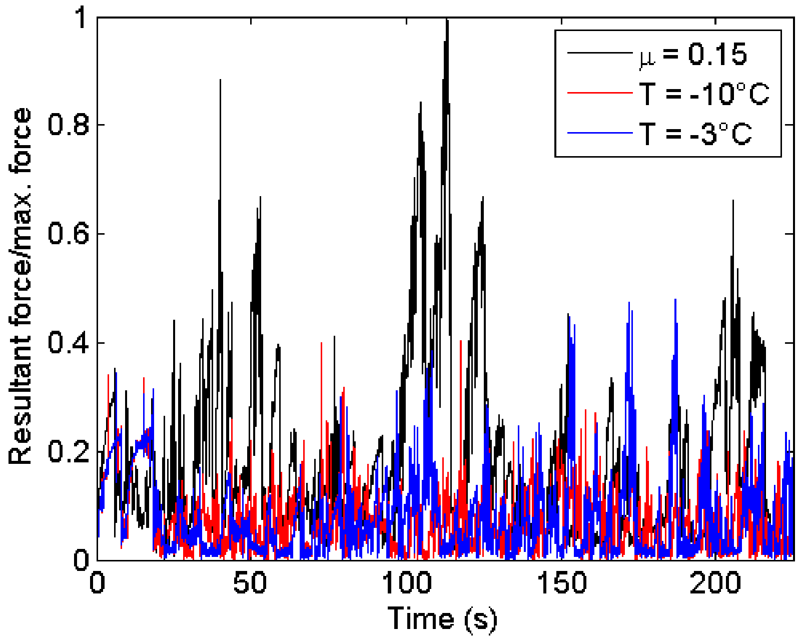

Figure 8. Time history of the resultant normal force against the structure in the direction of the motion simulated with the constant friction coefficient $\mu = 0.15$ and with the friction model presented here at temperatures -10 and -3°C.

CONCLUSIONS

The thermodynamic friction model presented in this paper explains remarkably well the experiments on ice-on-steel friction by Marmo *et al.* (2005). This encourages the use of the friction model rather than a constant friction coefficient in ice crushing simulations.

It was shown here by an example that the value of the friction coefficient is crucial when modelling the resultant normal force against the structure in ice crushing. Therefore, inclusion of ice friction modelling seems necessary for enhanced ice crushing simulations. The friction model can be further developed to consider saline sea ice. This will require understanding the presence of liquid brine on the surface of saline ice (Makkonen and Lehmus, 1987) and the possible difference in the hardness of fresh water ice and sea ice at the scale of the contacts.

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