Ice Friction (Prior Arts)

General frictional regimes [1]

- Dry friction: Sliding contact of two surfaces in absence of any kind of lubricating layer.
- Boundary friction: Sliding contact with a lubricating layer with the thickness of only a few molecular layers between the sliding surfaces. The thickness is less than the characteristic roughness of the surfaces.
- Mixed friction: Dry friction and boundary friction.
- Hydrodynamic friction: Everywhere the thickness of the lubricating layer between two surfaces is greater than the height of asperities.

![Friction regimes relevant to ice friction depending on the thickness of lubricating layer](image)

Figure: Friction regimes relevant to ice friction depending on the thickness of lubricating layer. *(I think this figure is a bit off on the coefficient of friction. The coefficient is measured to be about 0.01 for general ice skating. [2])*

Origin of the liquid-like layer on ice

Previous studies all agree on a liquid-like layer being the most important role in the low ice friction. The current research considers the primary origin for this liquid-like layer from frictional heating for high-speed sliding on ice with high enough pressure to lower the melting point of ice. In high-speed sliding (~5 m/s), the thickness of the liquid-like layer is measure to be about 50 micrometer.

- Surface melting: The existence of a liquid-like layer is an inherent part of the ice, which exists even without friction. Different techniques measured the thickness varies from 1 nm to 100 nm.
- Pressure melting: Pressure contributes to lower the melting point of ice.
- Frictional heating: Frictional heating is the main source for the formation of liquid-like layer on ice. *(I made a simple estimation of the thickness of the liquid layer generated by frictional heat. If all of the heat is used to melt ice into water, then a 500 micrometer layer could be formed, which means that the heat is by far enough to create the liquid-like layer as observed in experiments.)*
Lubricating film under a slider on ice becomes thicker toward the trailing end. The “leading edge” of the ice skate blade undergoes mixed friction (dry friction and boundary friction) all the time, which generates more than enough heat for ice melting. The heat generating power is

\[ \dot{q}_m = \frac{fu}{A} = \frac{\mu F_N u}{A} \]

where \( \dot{q}_m \) [W/m²] is the heat generated per meter square, \( \mu \) is the viscosity, \( F_N \) is the normal force, \( \mu \) is the sliding velocity, \( A \) is a constant depending on the actual contact area between the skate blade and ice.

The skate blade after the “leading edge” undergoes hydrodynamic friction. Heat generated in the liquid-like layer is

\[ \dot{q}_h = \eta \left( \frac{du}{dh} \right)^2 \]

where \( \dot{q} \) [W/m³] is the heat generated per meter cube, \( \eta \) [kg/(ms)] is the viscosity of the liquid-like layer, \( u \) is the local velocity, \( h \) is the layer thickness.

**Influence of different parameters on the friction coefficient**

Temperature \( T \): The coefficient of friction decreases first with increasing temperature and rises again when the temperature approaches 0 Celsius degree. The minimum coefficient is obtained between -2 and -7 Celsius degree depending on the normal load, the speed, and the slider material.

(a) Sliding velocity \( v \):

\( \mu \propto 1/\sqrt{v} \) (Experiments and models)

(b) Normal force \( F_N \): Most of the models did not yield good results. May be interesting for us to explore more?

\( \mu \propto \left( \frac{1}{\sqrt{F_N}} \sim \frac{1}{\sqrt{F_N}} \right) \) (Experiments)

(c) Apparent area of contact \( A \): Different hypothesis give different results. No good model yet. May be interesting for us to explore more?

\( \mu \) increases with the geometric contact area nonlinearly (Experiments)

(d) Roughness

\( \mu \) increases when the surface is less smooth

(e) Wettability

\( \mu \) increases when the surface is easier to wet
(f) Thermal conductivity

\[ \mu \text{ increases when the surface is higher conductivity} \]

Ice friction models

All previous models are based on theories of heat transfer. The general assumption is as the following:

(a) Liquid-like layer on ice accounts for the low friction of high speed sliding (~5 m/s).

(b) Most of the heat for ice melting is generated by friction.

(c) Most of the generated heat is conducted away. Less than 10 percent of the heat is used for ice melting.

First Model [4]: The total heat generated by friction is the sum of the heat conducted away through slider material and the ice, and the heat for melting the ice.

\[ F = F_s + F_i + F_M \]

where \( F \) is the total heat generated by friction, \( F_s \) is the heat conducted away from the interface through the slider material, \( F_i \) is the heat which diffuses to the ice, \( F_M \) heat needed for melting the ice surface.

Being divided by \( F_N \) on both sides gives coefficient of friction as below:

\[ \mu = \frac{A\lambda_s (T_m - T_0)}{F_N v} + \frac{B(T_m - T_0)}{F_N \sqrt{v}} + \mu_m \]

where \( T_m \) and \( T_0 \) being the melting and the ambient temperature, respectively. \( \lambda_s \) being the thermal conductivity of the slider, \( v \) being the sliding velocity, \( A \) being a constant depending on the actual contact area, and \( B \) being a constant depending on the actual contact area, \( F_N \) is the normal force.

Second Model [5]: Consider a heat source of intensity \( Q \) (flux per unit area) traveling over a half space. The temperature rise on the surface is:

\[ \Delta T = 2Q \left( \frac{t}{\pi k \rho c} \right)^{1/2} \]

where \( k, \rho, c \) are the thermal properties of the half space and \( t \) is the time for which the source has been over any point on the surface.

\[ t = B / v \] (\( B \) is the source of length \( B \) (in direction of sliding) travelling at velocity \( v \)), \( Q = \mu P v \) (\( P \) is the interface pressure). Plug in \( t \) and \( Q \), rearrange:

\[ \mu = C \frac{A_c (T_c - T_i)}{F_N} \left( \frac{\lambda_s \rho_s c_s}{v b} \right)^{1/2} \] (C constant)
where $T_C$ and $T_i$ being the temperature at the contact and the ice, respectively. $\lambda_s$ being the thermal conductivity of the slider, $v$ being the sliding velocity, $A$ being a constant depending on the actual contact area, $F_N$ is the normal force.

Primary Reference:


