Advanced numerical model for viscous friction between rough rubber and smooth ice

- Alessandro Scattina[1]
- Riccardo Leonardi[2]
- Salvatore Scalera[2]

[1]Politecnico di Torino, Dipartimento di Ingegneria Meccanica e Aereospaziale

[2]DYNAmore Italia S.r.l.

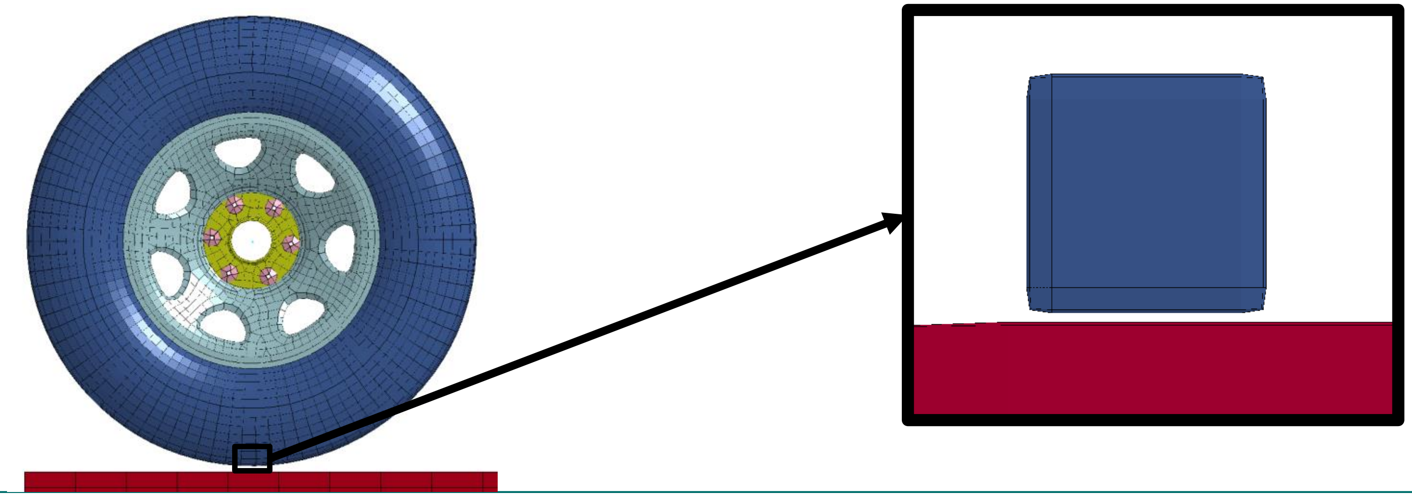
Contents

Introduction

- The purpose of this work is to simulate the contact between the rubber of the tire and the ice using a FEM model during the transient phase (the first $10\,ms$ of rubber-ice interaction)
- The transient phase is manly dependent on the micro-structural property of the rubber. For this reason this work follows a microscopic approach
- The main problems which can affect the numerical simulation are:
  - The phase changing of the ice due the energy that comes from the friction→ instability and discontinuity in the E.O.S.
  - The dimensions involved → high calculation time
- The *LS-DYNA User Defined Friction* was used to simulate the effects of the melting of the ice and the related hydrodynamic behaviours during the sliding of a rubber block

Macroscopic approach

Microscopic approach



Thermodynamic formulation

- A smooth rubber block that is sliding on an ice surface with a velocity v, loaded with a nominal pressure p_{nom}

heat from **viscous shear stress** | melting | conducted trough the ice

$$\eta_{water}\frac{v^2}{h(t)} = \rho\, L\frac{dh(t)}{dt} + \lambda\frac{T_m - T_0}{(\pi\ \alpha\ t)^{0.5}}$$

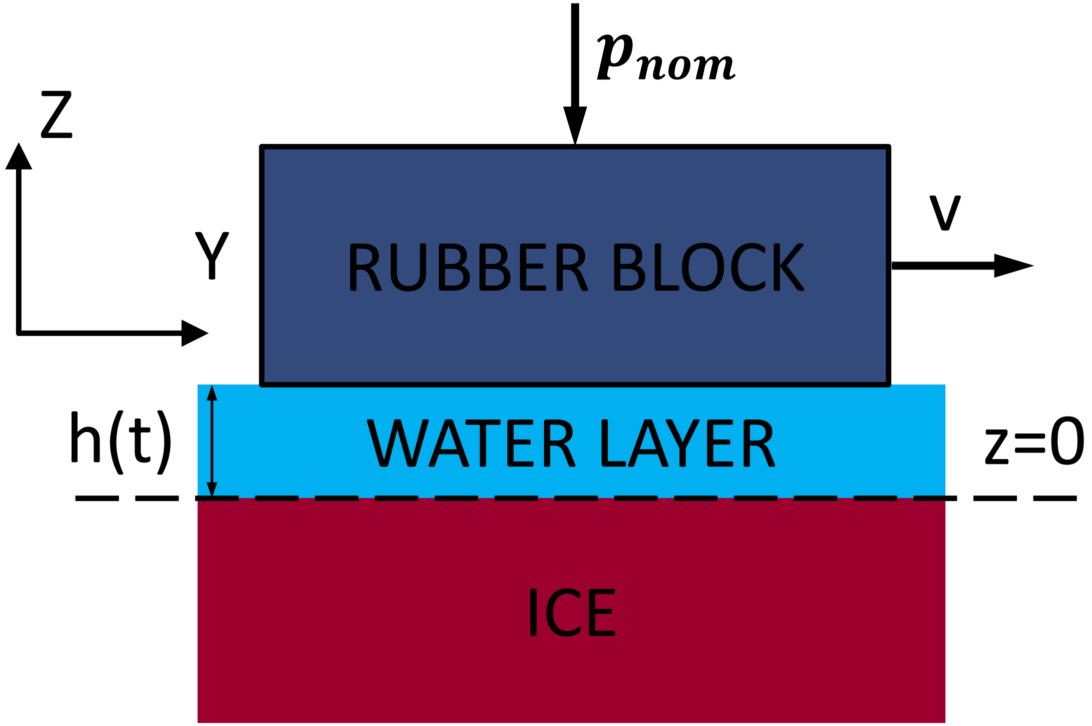
Thermodynamical balance

$$\frac{dh(t)}{dt} = \frac{1}{\rho\, L}\left(\eta_w\frac{v^2}{h(t)} - \lambda\frac{T_m - T_0}{(\pi\ \alpha\ t)^{0.5}}\right)$$

ODE for the height of the liquid layer

$$\mu(t) = \frac{\eta_w\, v}{h(t)\, p_{nom}}$$

Friction coefficient

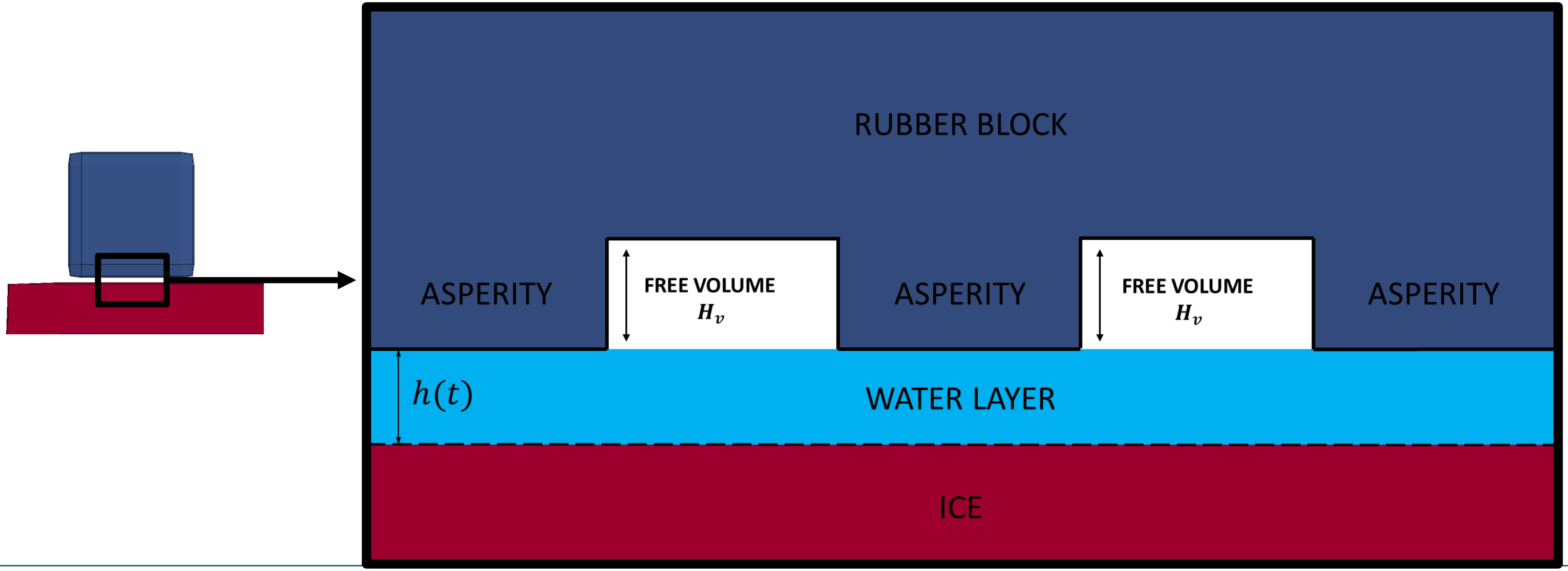


Thermo-hydrodynamic formulation

- Considering the roughness of the rubber surface, the equation for the height of the liquid layer becomes:

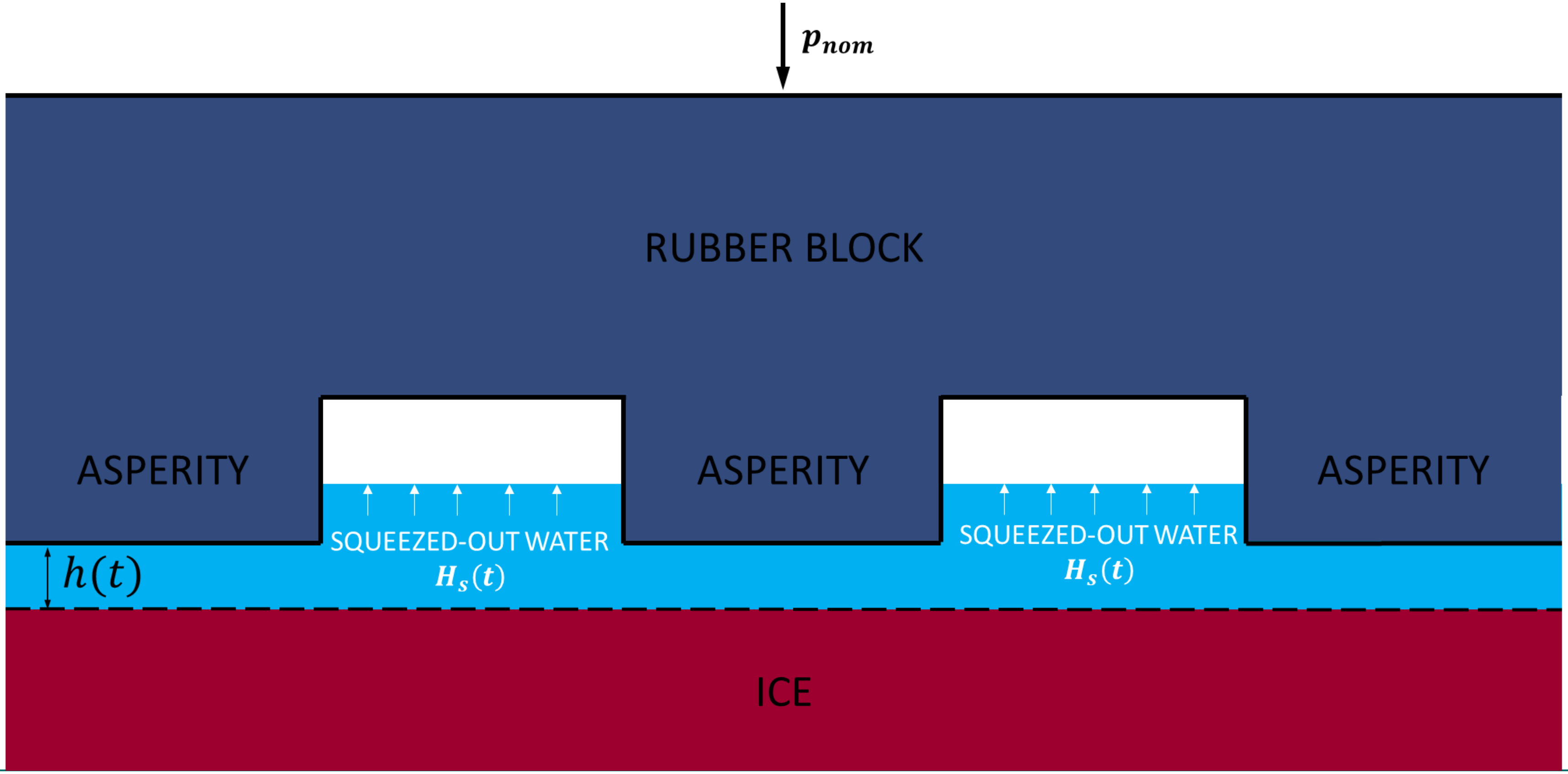
$$\frac{dh(t)}{dt} = \frac{1}{\rho\, L}\left(\eta_w k \frac{v^2}{h(t)} - \lambda \frac{T_m - T_0}{(\pi\, \alpha\, t)^{0.5}}\right) - \frac{8}{3\eta_w}\frac{p_{nom}}{D_{asp}^2} h(t)^3 \chi_{(\mathrm{H_{s(t)}} < \mathrm{H_v})}$$

hydrodynamic effects



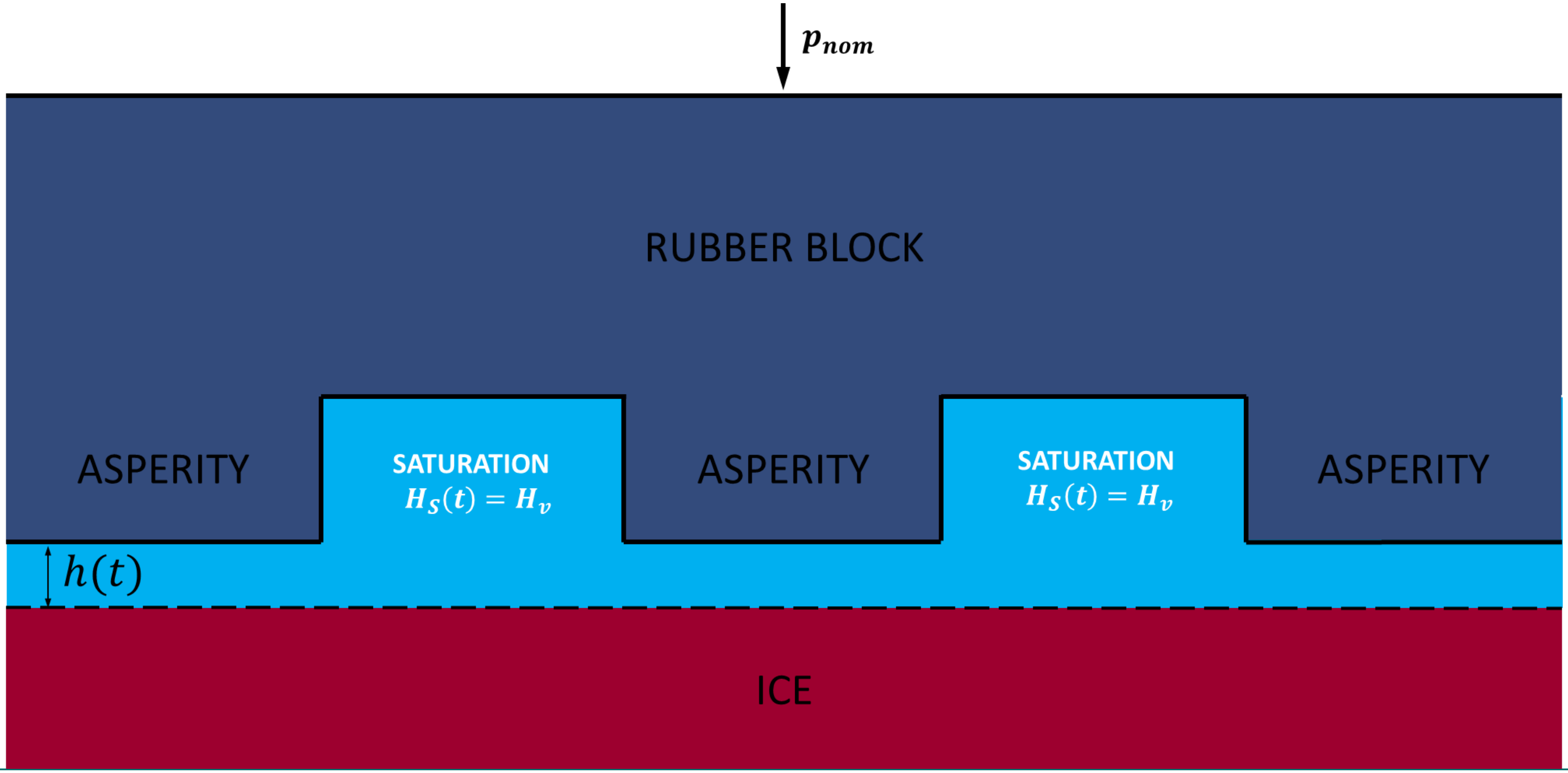
Thermo-hydrodynamic formulation

- The first hydrodynamic effect is the ***Squeeze-out*** effect:
  - the water is squeezed-out by the pressure of the asperities. The water layer decreases
  - the amount of the squeezed-out water is evaluated by the formula $\boldsymbol{H_s(t) = \frac{8}{3\eta_w}\frac{p_{nom}}{D_{asp}^2}\int_0^t h(t)^3\,dt}$



Thermo-hydrodynamic formulation

- The second hydrodynamic effect is the ***Saturation*** effect:
  - the free surface of the rubber is filled by the water $\boldsymbol{H_s(t) = H_v}$
  - $\boldsymbol{H_v}$ depends on the material characteristics and is experimentally evaluated



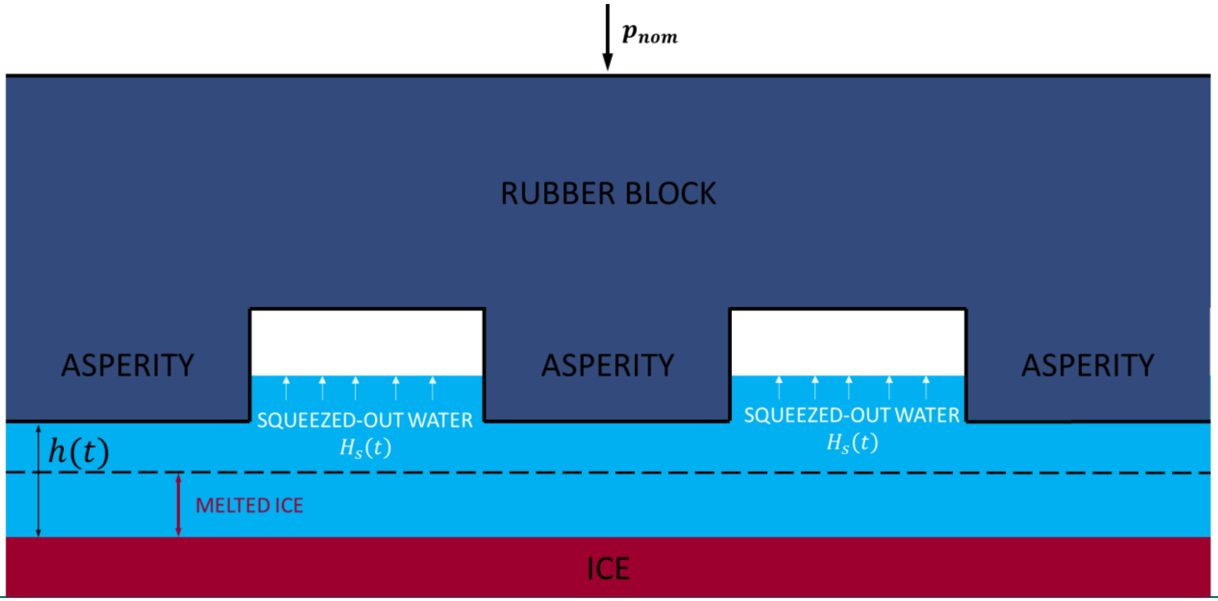
Thermo-hydrodynamic formulation for the transient phase

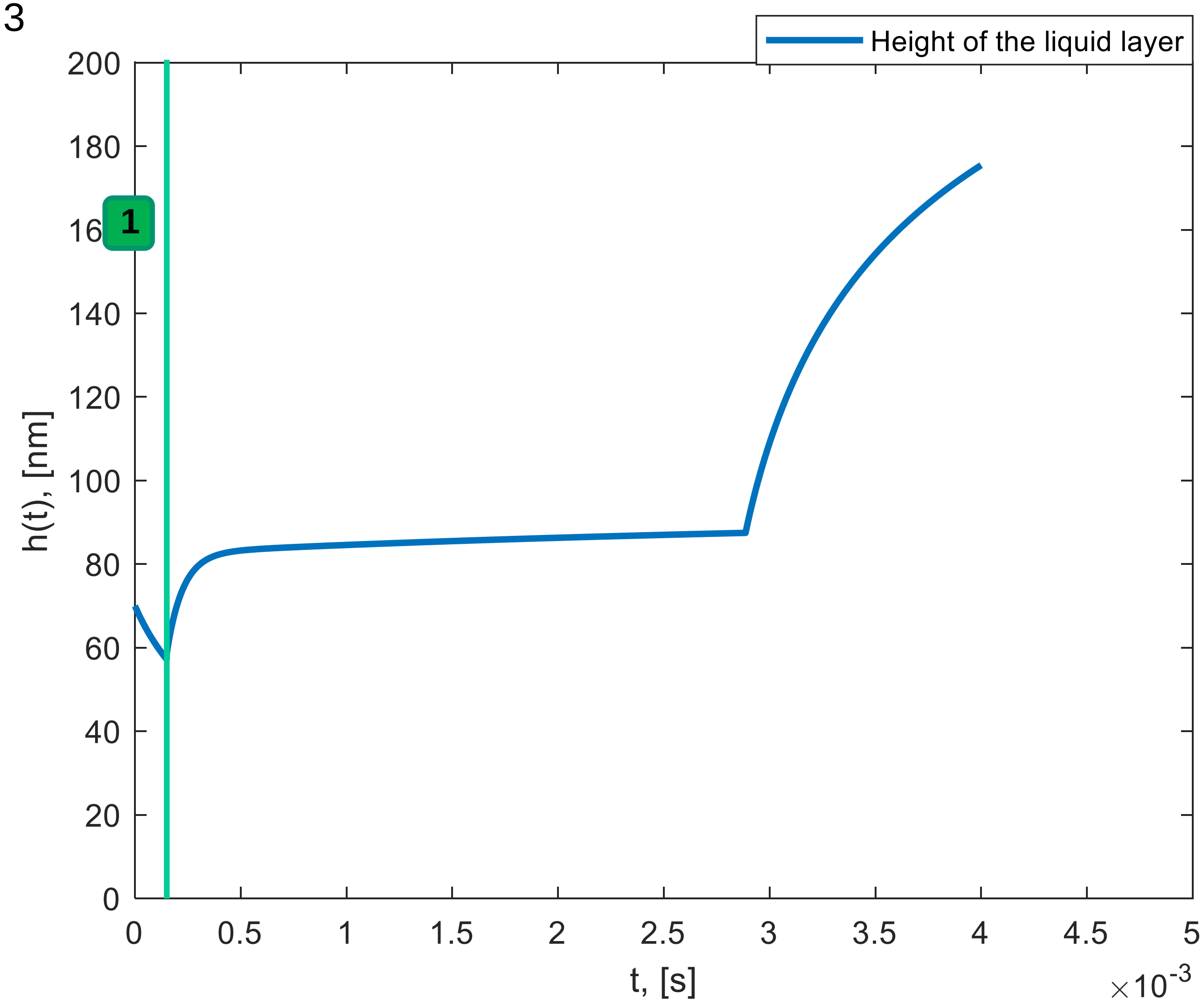
- From a graphical point of view, it is possible to distinguish 3 different phases during the sliding motion:

Squeeze-out effect

Phase 1, $T < T_m$, $H_s(t) < H_v$:

$$\frac{dh(t)}{dt} = -\frac{8}{3\eta_w}\frac{p_{nom}}{D_{asp}^2}h(t)^3$$





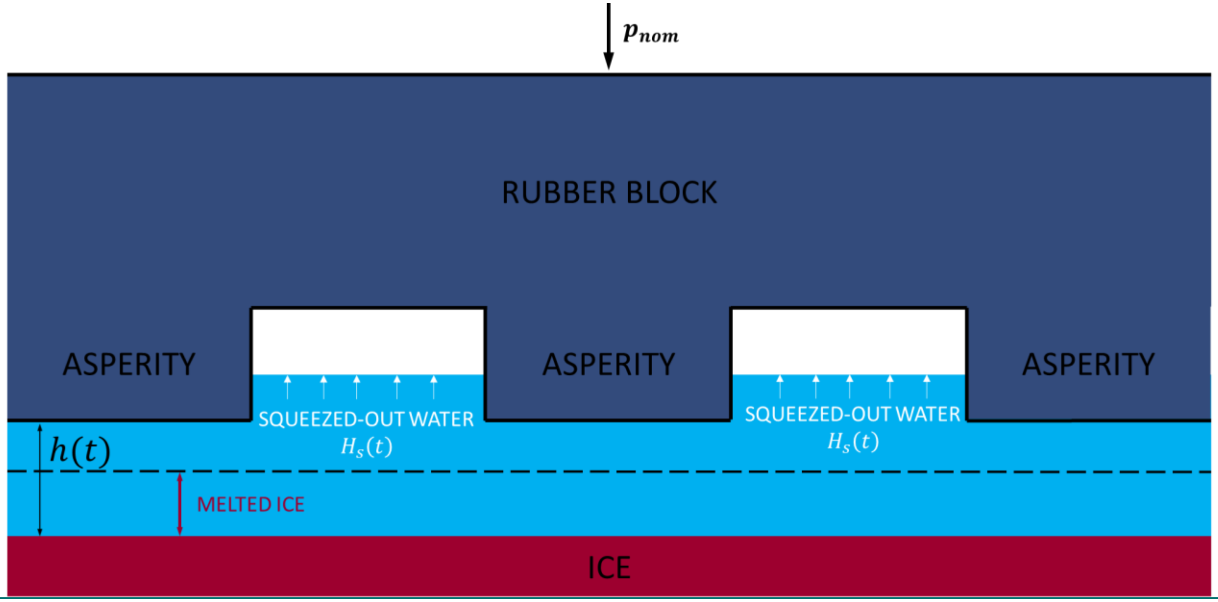
Thermo-hydrodynamic formulation for the transient phase

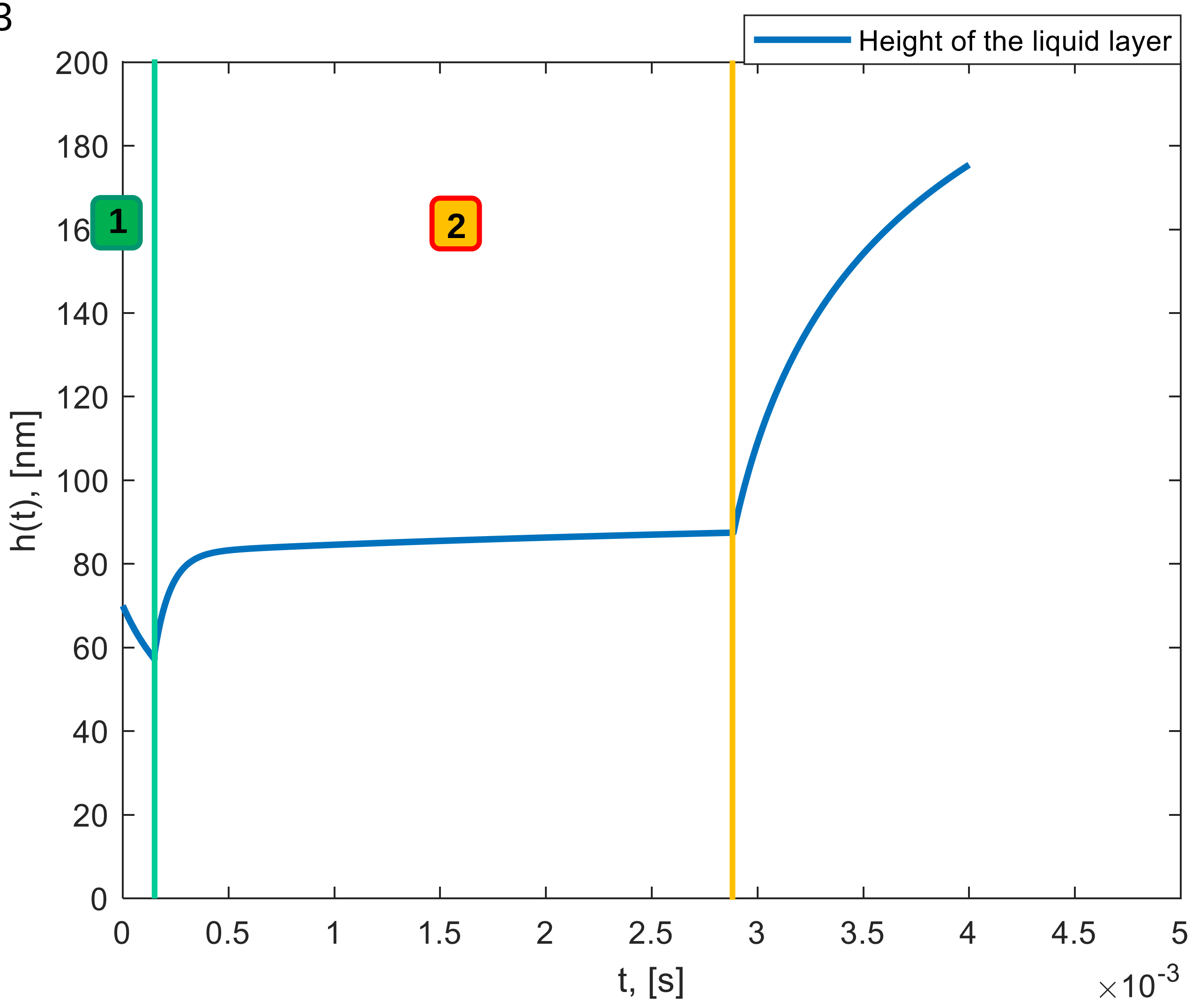
- From a graphical point of view, it is possible to distinguish 3 different phases during the sliding motion:

Squeeze-out effect and melting of the ice

Phase 2, $T = T_m , H_s(t) < H_v$:

$$\frac{dh(t)}{dt} = \frac{1}{\rho L}\left(\eta_w k \frac{v^2}{h(t)} - \lambda \frac{T_m - T_0}{\sqrt{\pi \alpha t}}\right) - \frac{8}{3\eta_w}\frac{p_{nom}}{D_{asp}^2} h(t)^3$$





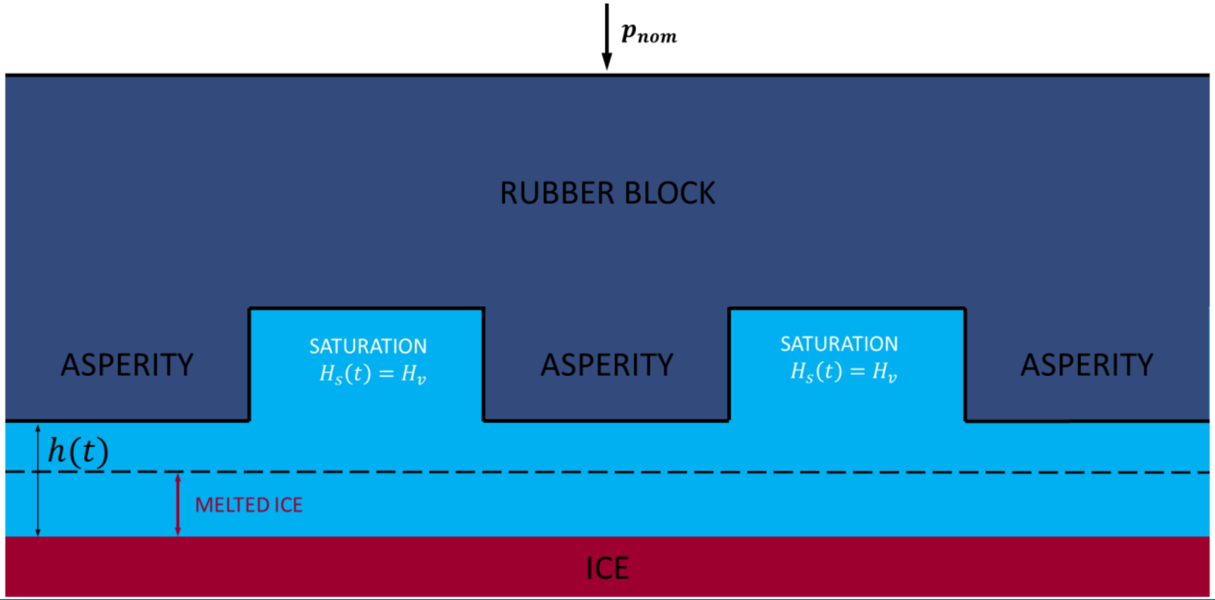
Thermo-hydrodynamic formulation for the transient phase

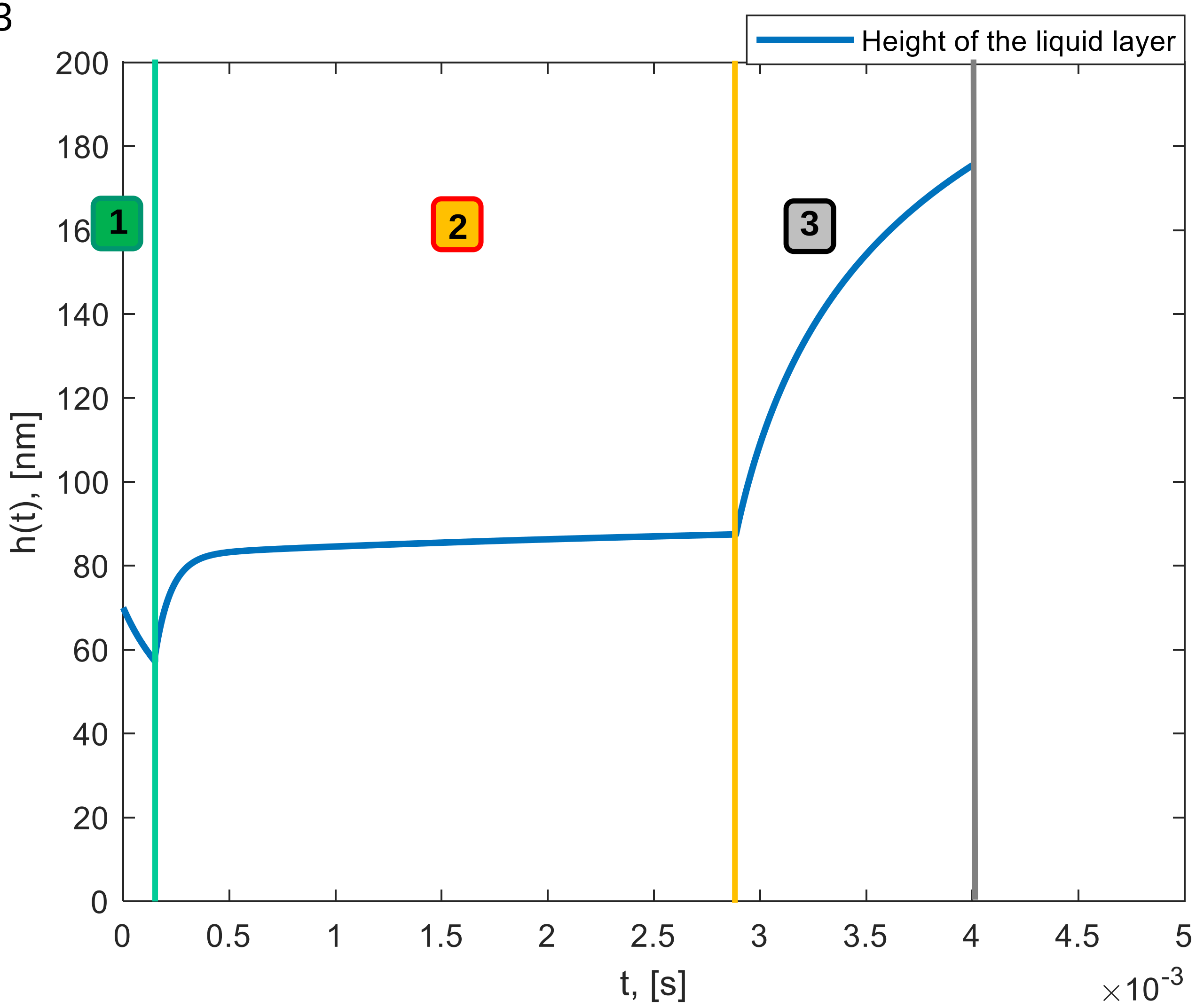
- From a graphical point of view, it is possible to distinguish 3 different phases during the sliding motion:

Saturation effect

Phase 3, $T = T_m, H_s(t) = H_v$:

$$\frac{dh(t)}{dt} = \frac{1}{\rho\, L}\left(\eta_w k \frac{v^2}{h(t)} - \lambda \frac{T_m - T_0}{\sqrt{\pi\, \alpha\, t}}\right)$$





Numerical Implementation

- For the implementation in the subroutine, it is necessary to solve the differential equation
- Explicit Euler was chosen for the numerical formulation

Generic derivative function

$$\frac{dh(t)}{dt} = f(t)$$

Incremental ratio

$$\frac{h_{j+1} - h_j}{dt} = f(t) + \varepsilon(t)$$

Numerical solution

$$h_{j+1} = h_j + dt\, f(t)$$

Phase 1

$$h_{j+1} = h_j - dt(\mathrm{K}_3\, \mathrm{h(t)}^3)$$

Phase 2

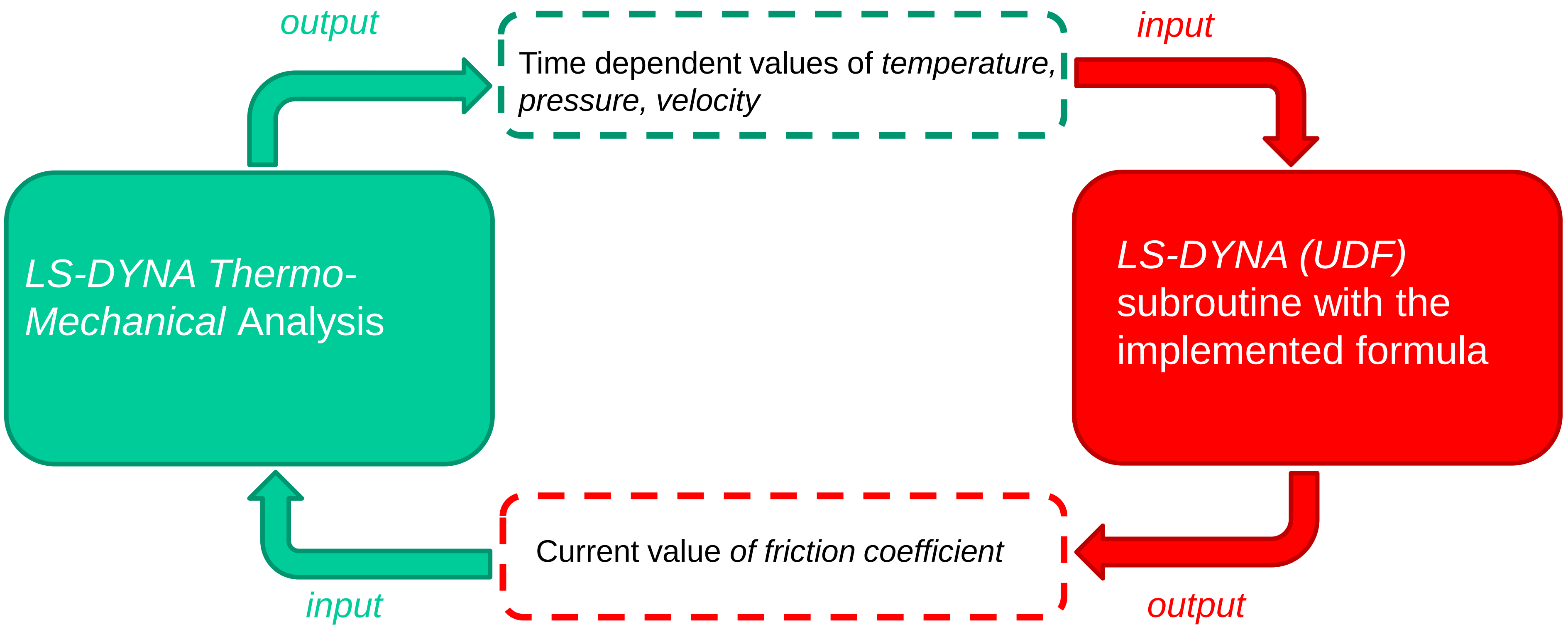
$$h_{j+1} = h_j + dt\left(\frac{\mathrm{K}_1}{\mathrm{h(t)}} - \frac{\mathrm{K}_2}{\sqrt{\mathrm{t}}} - \mathrm{K}_3\, \mathrm{h(t)}^3\right)$$

Phase 3

$$h_{j+1} = h_j + dt\left(\frac{\mathrm{K}_1}{\mathrm{h(t)}} - \frac{\mathrm{K}_2}{\sqrt{\mathrm{t}}}\right)$$

LS-DYNA model

- The numerical solutions are implemented in the subroutine which works in parallel with the ***LS-DYNA thermo-mechanical*** simulation :

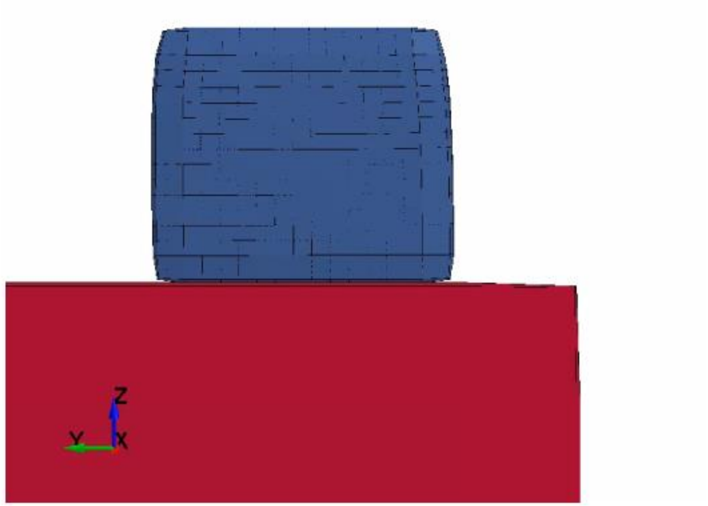


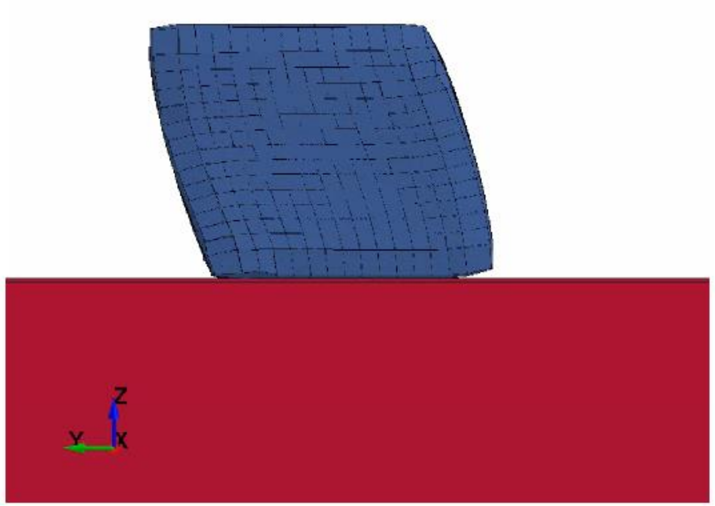
LS-DYNA model

- The simulation is composed by 2 phases:

1. **pre-load phase (via dynamic relaxation):**
   - the rubber block is loaded by a nominal pressure
   - after the rising of the equilibrium, a boundary condition for the velocity is assigned
   - a constant value of friction coefficient is assumed

2. **transient phase:**
   - the thermo-mechanical simulation and the *user define* subroutine work in parallel
   - a non-stationary friction coefficient is the results of the rubber-ice contact interaction

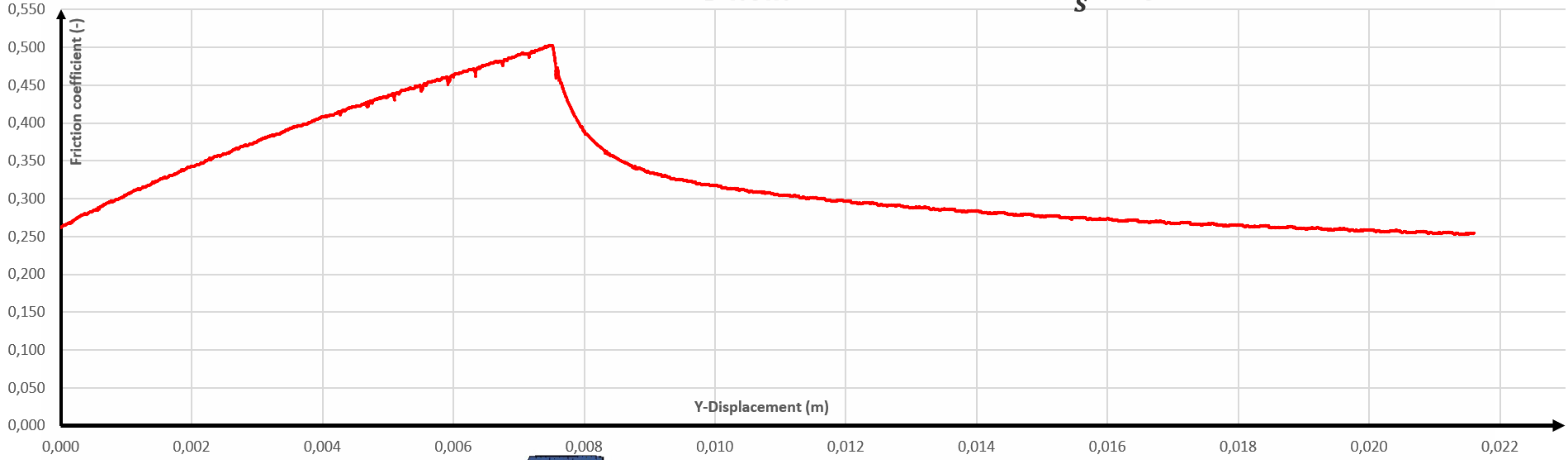




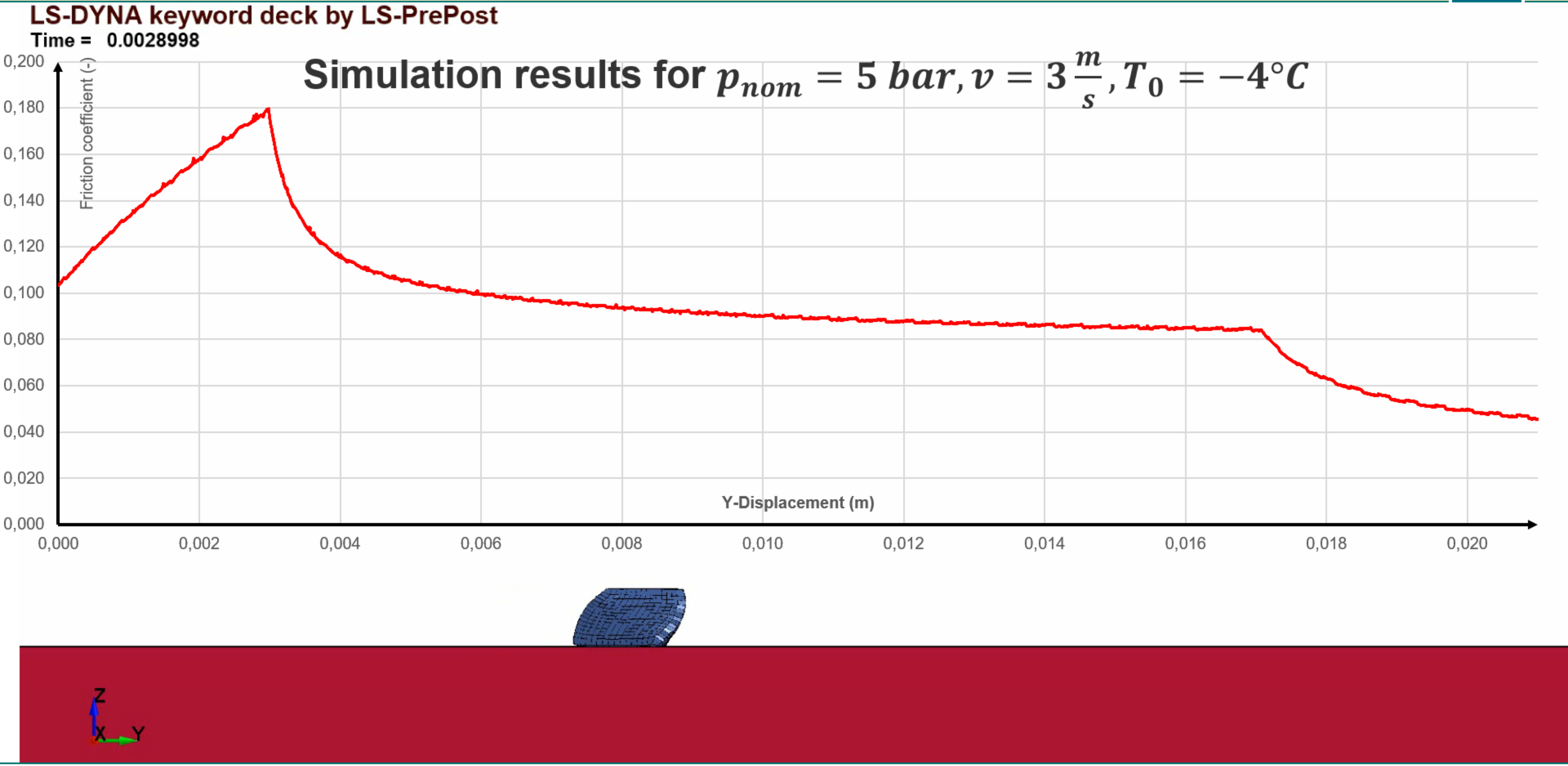
LS-DYNA keyword deck by LS-PrePost

Time = 0.0026996

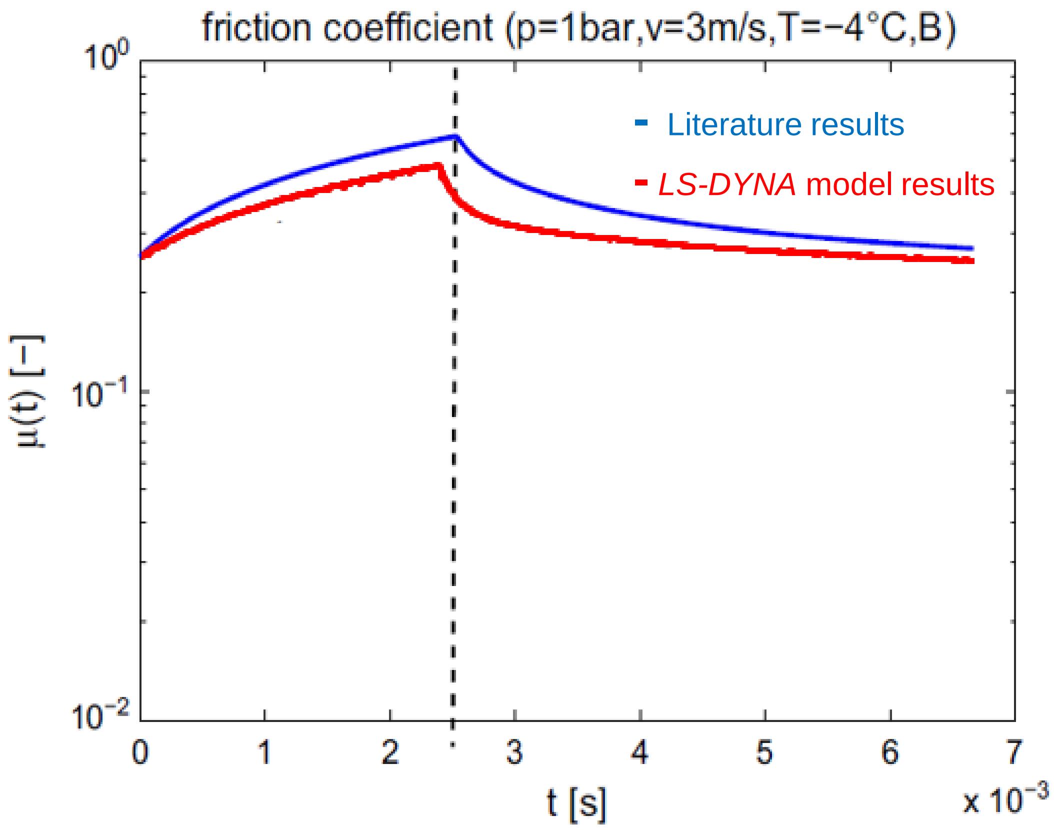
Simulation results for $p_{nom} = 1\ bar, v = 3\frac{m}{s}, T_0 = -4°C$

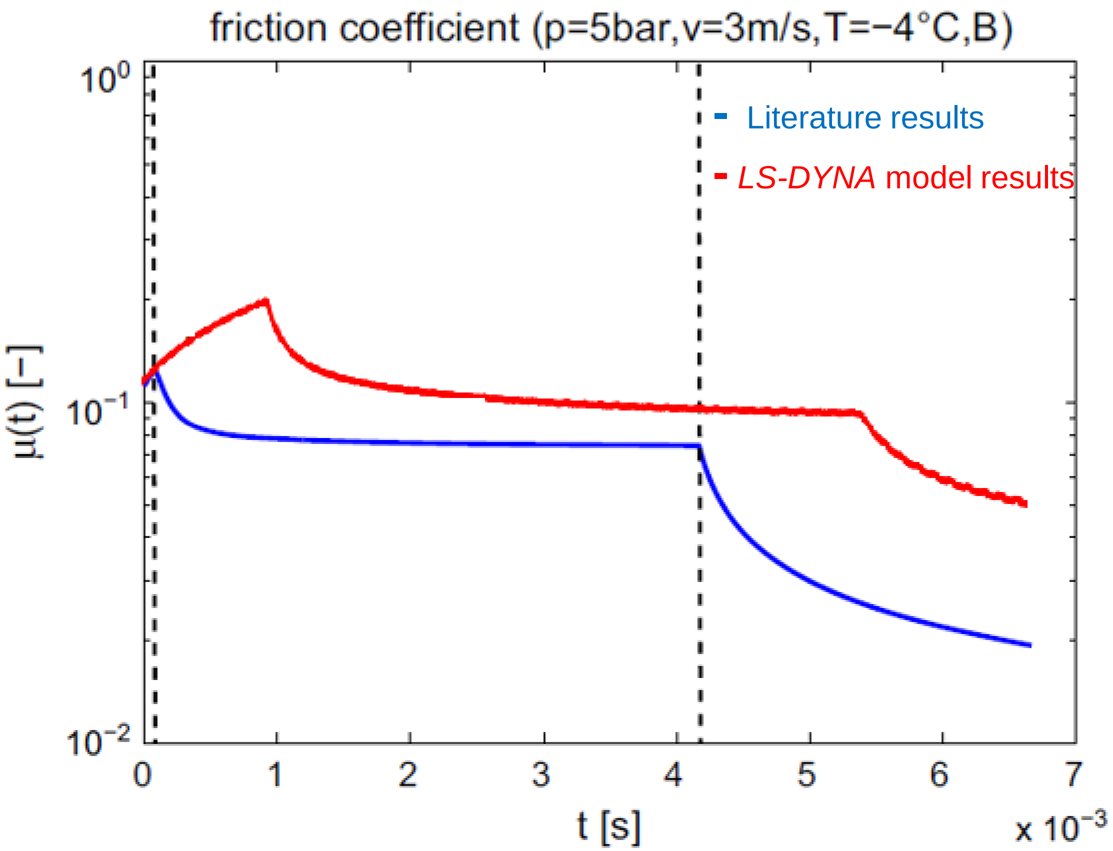


Simulation results for $p_{nom} = 5\ bar, v = 3\frac{m}{s}, T_0 = -4°C$



Comparison with the reference results





Conclusions

- The transient value of the friction coefficient of the rubber-ice sliding contact was studied from a microscopic point of view
- The *LS-DYNA UDF* was used to simulate the effects of the melting of the ice and the related hydrodynamic behaviours during the sliding of a rubber block
- A good agreement with the literature results was obtained both for a load of 1 bar and 5 bar was obtained. A further investigation about material parameters will be necessary
- Future developments, in agreement with the customer’s request, will be the possibility to include also the macroscopic hydrodynamic effects during the subsequent steady-state phase
- The application of this methodology to a whole tire is the final step

Thank you for the attention