Parameter sheet for InterFrost Test Case TH2 "Frozen Inclusion"

(Version 2.0, 4th Febr. 2015)

Geometrical features, boundary conditions and parameter sets are provided below as well as performance measures.

Geometrical features

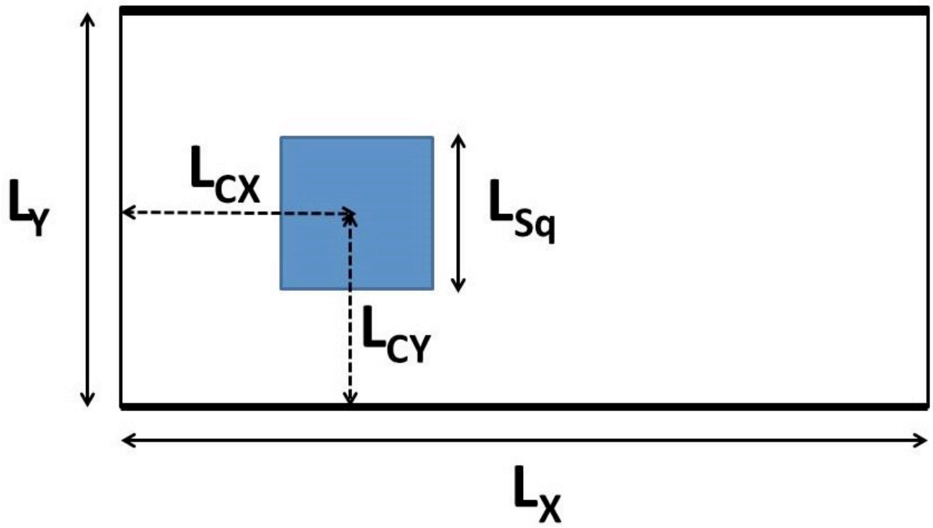

FIGURE 1 – Geometrical setup for TH2 Test Case

Symbol	Description	Value	Unit
L_x	Longitudinal extension of the simulated domain	3	m
L_y	Lateral extension of the simulated domain	1	m
$(L_{cx}; L_{cy})$	Postion of the inclusion center	$(1; 0.5)$	m
L_{sq}	Size of the square shaped inclusion	0.333	m

TABLE 1 – Geometrical parameter values for TH2 Test Case

Boundary and initial conditions

Initial temperature conditions are provided in Fig. 3 : $-5^{\circ}C$ in the square inclusion and $+5^{\circ}C$ in the rest of the domain. This temperature field is Boolean. The initial pressure and velocity field result from a steady state flow simulation with the permeability field associated with the initial temperature field and the pressure/head boundary conditions provided in Fig. 2.

The downstream right boundary condition for heat transfer is an imposed zero conductive flux condition. This means that the heat exits the system purely by advection. Refer to Fig. 3 for conditions on other boundaries. The values of the imposed head gradient are varied in a sensitivity analysis to the advection term in the exercise (refer to Tab. 2).

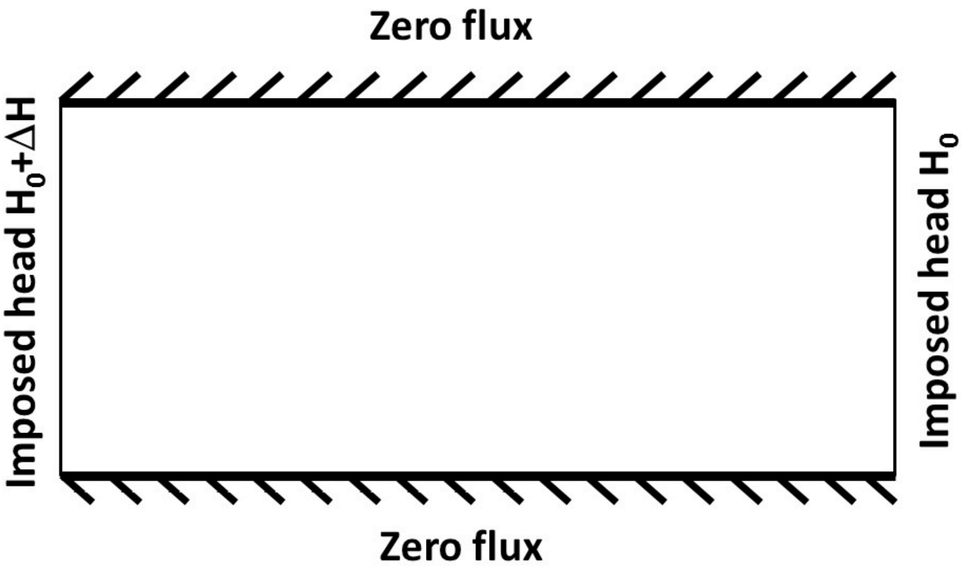

FIGURE 2 – Water flow boundary conditions

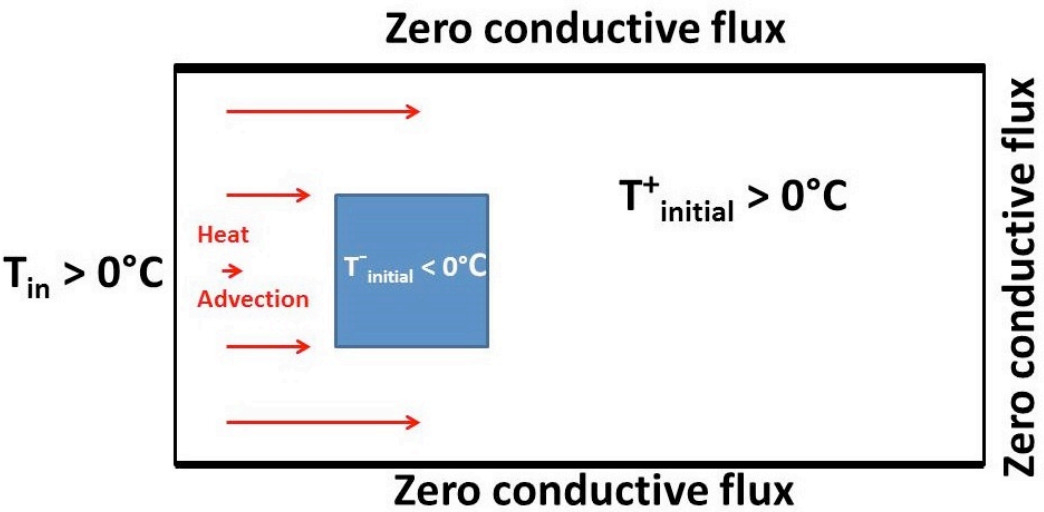

FIGURE 3 – Heat transfer boundary conditions and thermal initial condition

Symbol	Description	Value	Unit
$T^{-}_{initial}$	Initial temperature of the frozen inclusion	-5	$^{\circ}C$
$T^{+}_{initial}$	Initial temperature of the thawed domain	$+5$	$^{\circ}C$
T_{in}	Temperature on the incoming flow	$+5$	$^{\circ}C$
$\Delta H/L_x$	Hydraulic head gradient 1	0	$(-)$
$\Delta H/L_x$	Hydraulic head gradient 2	0.03	$(-)$
$\Delta H/L_x$	Hydraulic head gradient 3	0.09	$(-)$
$\Delta H/L_x$	Hydraulic head gradient 4	0.15	$(-)$

TABLE 2 – Initial and boundary conditions for temperature and suggested hydraulic head gradients for TH2 Test Case

Equations

Equations solved in our Cast3M code for this test case are provided here. We kindly ask participants to adopt a similar model to allow easy inter-comparison.

Flow equation (Eq. 1) :

$$(S_w \epsilon \rho_w g \beta)\frac{\partial p}{\partial t} = \vec{\nabla} \cdot \left(\mathbf{K_w}(\vec{\nabla} p + \vec{\nabla} z)\right) + \left(\epsilon \frac{\rho_i - \rho_w}{\rho_w}\frac{\partial S_w}{\partial t}\right) \quad (1)$$

Heat transfer (Eq. 2) :

$$\left(\epsilon(S_w \rho_w C_w + S_i \rho_i C_i) + (1-\epsilon)\rho_s C_s + \epsilon \rho_i L \frac{\partial S_w}{\partial T}\right)\frac{\partial T}{\partial t} = \vec{\nabla} \cdot (\lambda_{\mathbf{eq}} \vec{\nabla} T) + \vec{\nabla} \cdot \left(\rho_w C_w T \, \mathbf{K_w}(\vec{\nabla} p + \vec{\nabla} z)\right) \quad (2)$$

Subscripts denote w for water, i for ice, s for solid matrix. Unknowns are p for pressure expressed in meters ($p = P/\rho_w g$, with P pressure in Pascal) and T for temperature ($^\circ K$).

Please note that :

- for the sake of simplicity no dispersion term is included in the conductive term.
- still for the sake of simplicity, no temperature dependence for water density or water viscosity was introduced. The ρ_w and μ parameters in Tab. 3 are fixed values.
- compressibility β (see Tab. 3) is an equivalent value combining liquid, solid and matrix compressibility.
- considering the symmetry of the problem, one may only model the upper or lower half of the domain.

Performance measures

Performance measures for code results inter-comparison are :

- **PF1** : Plot the evolution of the minimum of the simulated temperature field as a function of time. Practically speaking it is located at the centre of the inclusion as long as its temperature is below zero.
- **PF2** : Plot the evolution of the total heat flux exiting the system (right / downstream boundary) as a function of time.
- **PF3** : Plot the evolution of the total liquid water volume in the domain as a function of time.

A parameter sensitivity study is proposed to vary flow velocities with a series of imposed head gradient values (see Tab. 2). So these performance measures should be provided for these 4 flow regimes on the same graph and excel file.

Another sensitivity study is suggested as an option. It concerns the W parameter in the $S_w(T)$ law providing larger or smaller "mushy zones". The unique value of 0.5 is proposed in Tab. 3, corresponding to a B_t value of roughly $-1°C$ for the linear law (see [McKenzie et al. 2007], mushy zone extends from $0°C$ to $-1°C$). However two other values are suggested : 1.87 corresponding roughly to a B_t of $-4°C$ and 0.05 corresponding to a B_t value of $-0.1°C$. These runs should be considered for the base case head gradient of 0.03. The performance measures associated with these 3 values should be plot together on a separate graph.

Parameter values

Symbol	Description	Value or expression	Unit
ϵ	Porosity	0.37	$(-)$
β	Compressibility	10^{-8}	Pa^{-1}
g	Acceleration of Gravity	9.81	$m.s^{-2}$
λ_w	Water thermal conductivity	0.6	$W.m^{-1}.K^{-1}$
λ_i	Ice thermal conductivity	2.14	$W.m^{-1}.K^{-1}$
λ_s	Solid matrix thermal conductivity	3.5	$W.m^{-1}.K^{-1}$
λ_{eq}	Equivalent thermal conductivity	$\epsilon\big(S_w\lambda_w + (1-S_w)\lambda_i\big) + (1-\epsilon)\lambda_s$	$W.m^{-1}.K^{-1}$
C_w	Water Heat capacity	4182	$J.kg^{-1}.K^{-1}$
C_i	Ice Heat capacity	2060	$J.kg^{-1}.K^{-1}$
C_s	Solid matrix heat capacity	835	$J.kg^{-1}.K^{-1}$
ρ_w	Water volumetric mass	1000	$kg.m^{-3}$
ρ_i	Ice volumetric mass	920	$kg.m^{-3}$
ρ_s	Solid matrix volumetric mass	2650	$kg.m^{-3}$
$(\rho C)_{eq}$	Equivalent volumetric Heat capacity	$\epsilon\big(S_w\rho_w C_w + (1-S_w)\rho_i C_i\big) + (1-\epsilon)\rho_s C_s$	$J.m^{-3}.K^{-1}$
μ	Water dynamic viscosity	$1.793\,10^{-3}$	$kg.m^{-1}.s^{-1}$
L	Latent heat	$3.34\,10^{5}$	$J.kg{-1}$
$S_w(T)$	Water saturation for $T \geq 273.15$	1	$(-)$
$S_w(T)$	Water saturation for $T < 273.15$	$(1-S_{wres})e^{-((T-273.15)/W)^2} + S_{wres}$	$(-)$
S_{wres}	Residual saturation in $S_w(T)$	0.05	$(-)$
W	Parameter in $S_w(T)$	0.5	K
K_w	Permeability	$k_r k_{int}\rho_w g/\mu$	$m.s^{-1}$
k_{int}	Intrinsic permeability	$1.3\,10^{-10}$	m^2
$k_r(S_w)$	Relative permeability	$10^{-\Omega\epsilon(1-S_w)}$ if $k_r(S_w) > 10^{-6}$	$(-)$
$k_r(S_w)$	Relative permeability	10^{-6} if $k_r(S_w) \leq 10^{-6}$	$(-)$
Ω	Impedance factor	50	$(-)$

Table 3 – Physical parameter values and expressions considered for TH2 Test Case