Kick off meeting of INTERFROST, 18/10/14 Paris

INTERFROST : First test cases treated with OpenFOAM®

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INTERFROST: A benchmark of Thermo-Hydraulic codes for cold regions hydrology

Christophe Grenier[1], Nicolas Roux[1&2], François Costard[2], Marc Pessel[2]
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[1]LSCE - UMR 8212 CEA-CNRS-UVSQ, Orme des Merisiers, 91191 Gif sur Yvette Cedex [2]GEOPS, UMR 8148 CNRS - Université Paris Sud, 91405 Orsay Cedex, France

Context and objectives

Large focus was put recently on the impact of climate changes in boreal regions due to the large amplitudes expected. Large portions of these regions, corresponding to permafrost areas, are covered by water bodies (lakes, rivers) with very specific evolution and water budget. These water bodies generate taliks (unfrozen zones below) that may play a key role in the context of climate change.
Recent studies and modeling exercises showed that a fully coupled 2D or 3D Thermo-Hydraulic (TH) approach is required to understand and model the evolution of river and lake systems in a changing climate.
However, 3D studies are still scarce while all numerical approaches can only be validated against analytical solutions for a purely thermic equation with phase change (e.g. Neumann/Stefan, Lunardini). When it comes to the coupled TH system (coupling two highly non-linear equations), the only possible approach is to compare different codes on provided test cases and/or to have controlled experiments for validation and propel discussions to try and improve the code performances.
We propose here a benchmark exercise, detail some of its planned test cases and invite other research groups to join. The benchmark will consist of some test cases inspired by existing literature (e.g. Mc Kenzie et al., 2007) as well as new ones. Some experimental cases in cold room will complement the validation approach. The benchmark is open as well to new or alternative cases reflecting a numerical or a process oriented interest or answering a more general concern among the cold region community.
A further purpose of the benchmark exercise is to propel discussions for the optimization of codes and numerical approaches in order to develop validated and optimized simulation tools allowing in the end for 3D realistic applications.

Strategy, work plan

- For the test cases we will proceed from simple to complex, progressively including:
  - The various terms of the system of equations (pure thermal transfers to full coupling)
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T1: Lunardini/Osterkamp

Analytical solution:

1D semi-infinite, purely thermal conduction, phase change, cst. properties

Temperature profiles (Cast3M code vs Lunardini solution)

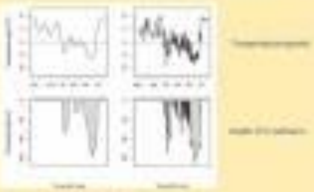
T2: Heterogeneous

Multi-layered, bounded, with geothermal flux.

Include field monitoring data.

T3: geological times

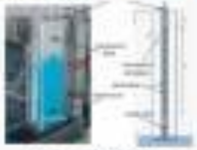
Heterogeneous, with geothermal flux, long simulation times



[illegible] 2013

T→P: 1D P↑

Experiments in cold room



Lemieux et al. 2011

Facility at GEOPS with controlled room temperature

Coupled system of TH equations

Darcy water flow equation

$$\left(S_w\frac{\partial(\varepsilon\rho_w)}{\partial p}\right)\frac{\partial p}{\partial t}=\nabla\cdot\left[\rho_w K_w\vec{\nabla}p\right]+\nabla\cdot\left[\rho_w K_w\vec{\nabla}z\right]-\left[\varepsilon(\rho_w-\rho_i)\frac{\partial S_w}{\partial T}\right]\frac{\partial T}{\partial t}+Q_w$$

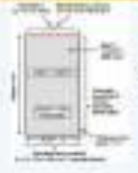
Heat transfer equation

$$\left(\rho_w S_w c_w\varepsilon+\rho_i S_i c_i\varepsilon+(1-\varepsilon)\rho_s c_s\right)\frac{\partial T}{\partial t}=$$

$$\nabla\cdot\left[\lambda\vec{\nabla}T\right]+\nabla\cdot\left[h_w\rho_w K_w\vec{\nabla}p+h_w\rho_w K_w\vec{\nabla}z\right]-\frac{\partial S_i}{\partial t}(\varepsilon\rho_i L)-\left[h_w S_w\frac{\partial(\varepsilon\rho_w)}{\partial p}\right]\frac{\partial p}{\partial t}+Q_h$$

The system is similar to the one of (Mc Kenzie et al., 2007)

TH1: Kurylyk & Lunardini

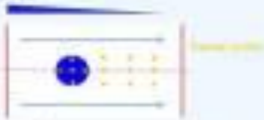


Analytical solutions including constant advection

TH2: Frozen inclusion

An initially 2D cold (T < 0°C) permafrost inclusion is present within a uniform water flow (T > 0°C)

Performance measurements are: 1°) time for the minimum system temperature to reach 0°C, 2°) temperature profiles along main axis for a set of control times



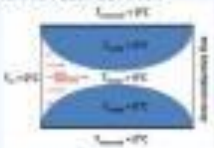
Longitudinal temperature profiles (Cast3M code)

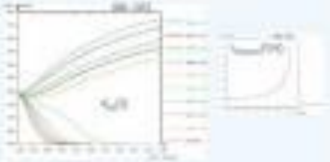
Evolution of minimal temperature [illegible]

TH3: Talik evolution

An initially 2D cold (T < 0°C) permafrost zone is present within a uniform water flow (T > 0°C). Imposed T < 0°C for upper and lower boundaries

Performance measurements are: 1°) equivalent permeability evolution, 2°) time for the talik to close for weak advection levels





Please join! … and come to discuss the cases!

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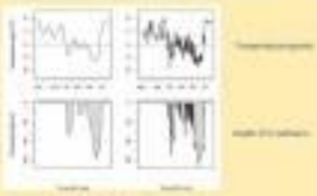

Mc Kenzie, 2012

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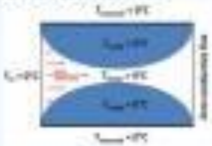

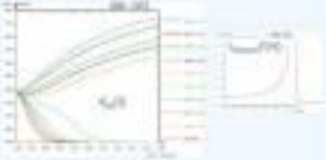

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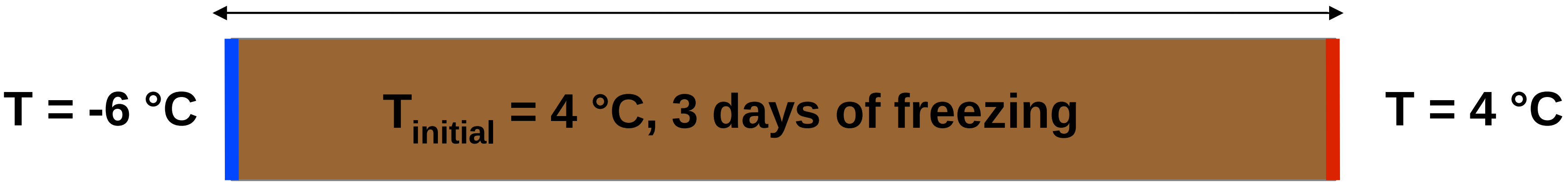
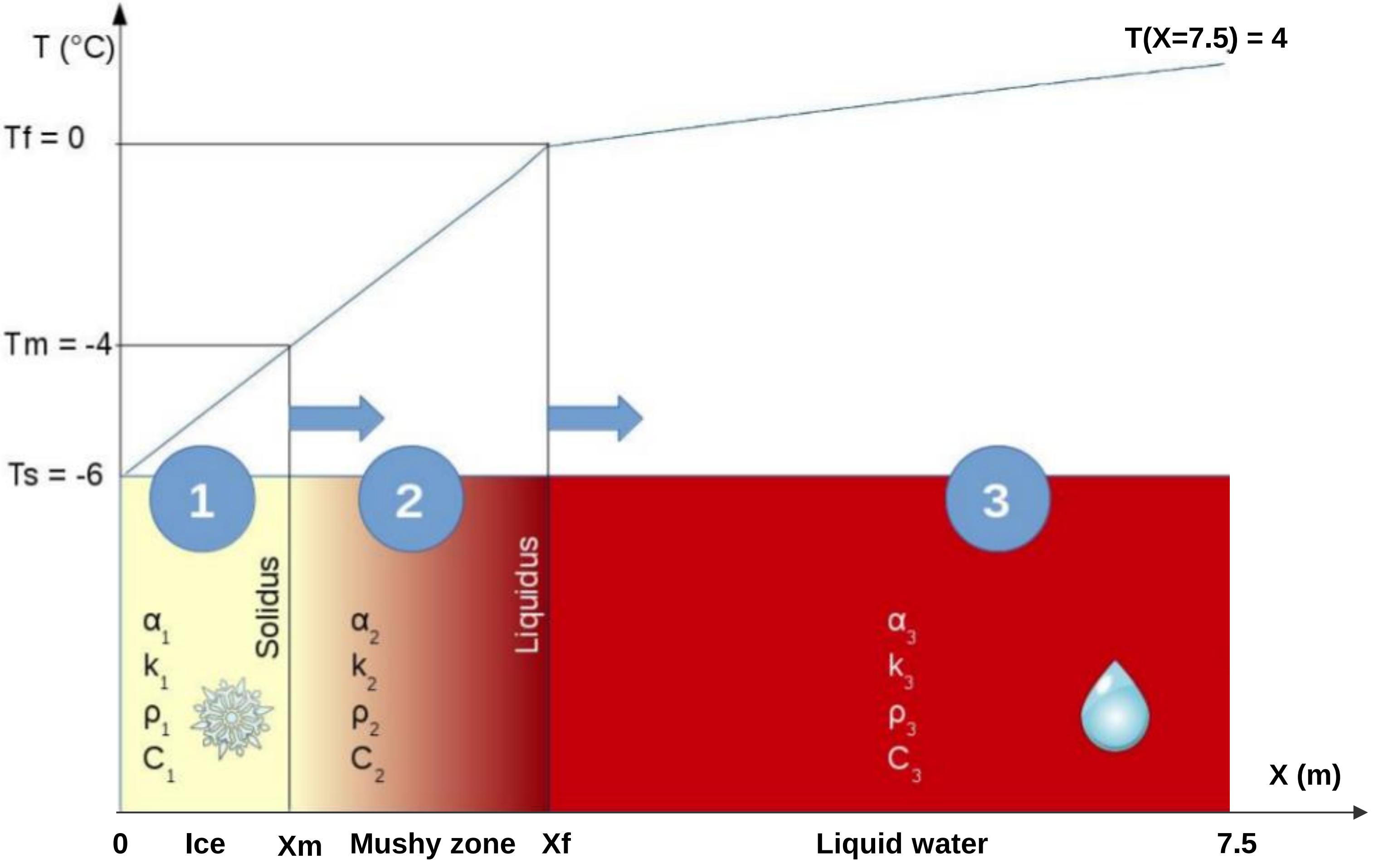
The purely conductive Lunardini case, McKenzie et al. 2007
1D transient analytical solution for thermal transfer / phase changes

1D geometry, Length 7.5 m





(Interfrost website, https://wiki.lsce.ipsl.fr/interfrost/doku.php?id=home)

The purely conductive Lunardini case, McKenzie 2007
1D transient analytical solution for thermal transfer / phase changes

Conservation equation:

$$C_n \frac{\partial T}{\partial t} = K_n \triangle T + L \frac{\partial \theta_{ice}}{\partial t} \;, \; n = liquid\, zone / \, mushy\, zone \, / \, icy\, zone$$

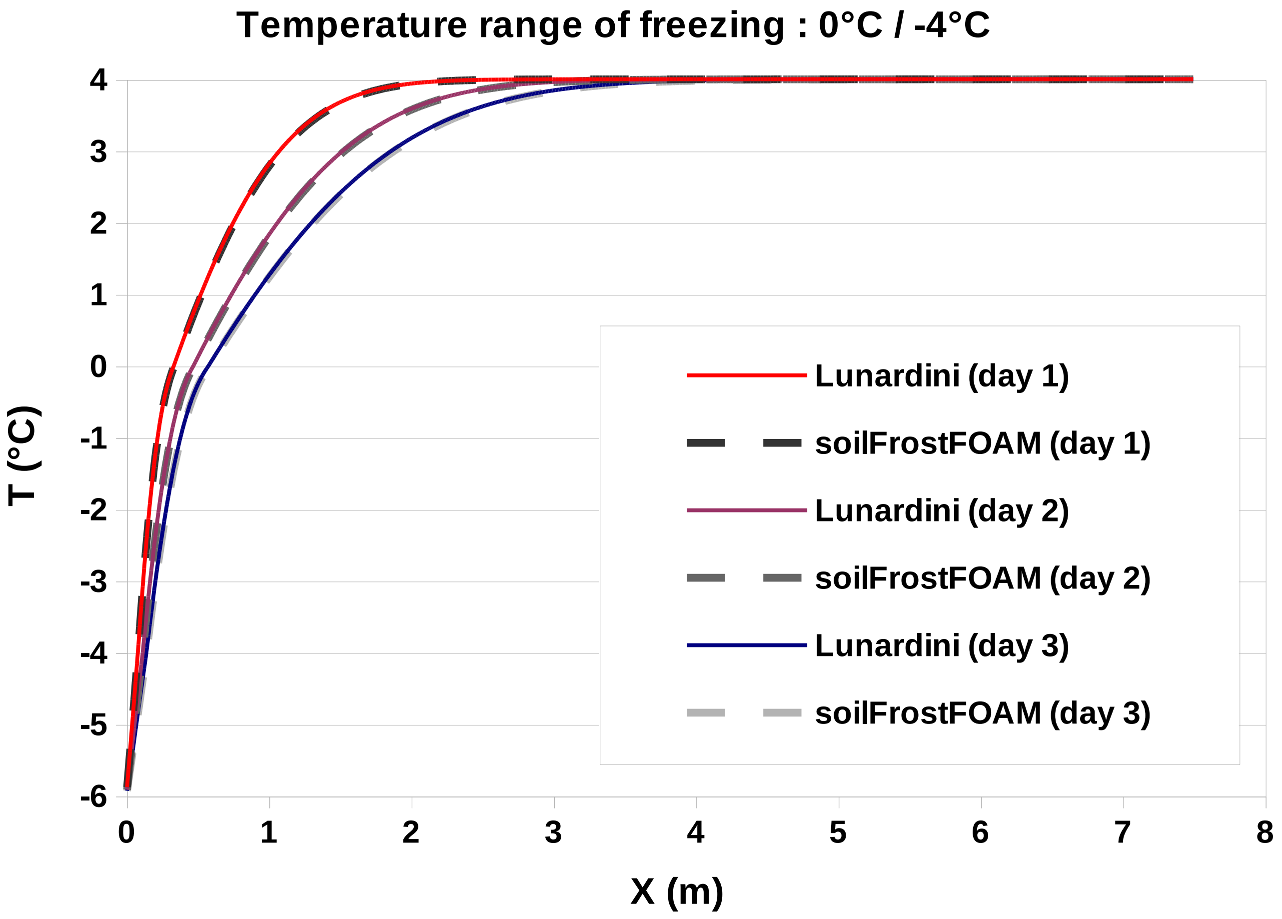
Phase changes:

$$\theta_{liquid} + \theta_{ice} = \theta_s$$

$$\theta_{ice} = \begin{cases} 0 \; if \, T > T_f \\ (\theta_s - \theta_r) \left(\frac{T - T_f}{T_f - T_m} \right) \\ \theta_s \; if \, T < T_m \end{cases}$$

T temperature [K], T_f starting temperature of water freezing [K], T_m starting temperature of ice melting [K], t time [s], C_n volumetric heat capacity [kg.m.s^{-3}.K^{-1}] of zone n, K_n thermal conductivity [kg.m.s^{-3}.K^{-1}], L latent heat of fusion of ice [kg.m^{-1}.s^{-2}], θ_{liquid} volumetric fraction of liquid water [-], θ_{ice} volumetric fraction of ice [-], θ_s saturated volumetric fraction of liquid water [-], θ_r residual volumetric fraction of liquid water [-].

The purely conductive Lunardini case:
1D transient analytical solution for thermal transfer / phase changes



Error max (T, °C) : <0.04

Mesh cell size : 1e-2 m (750 cells)

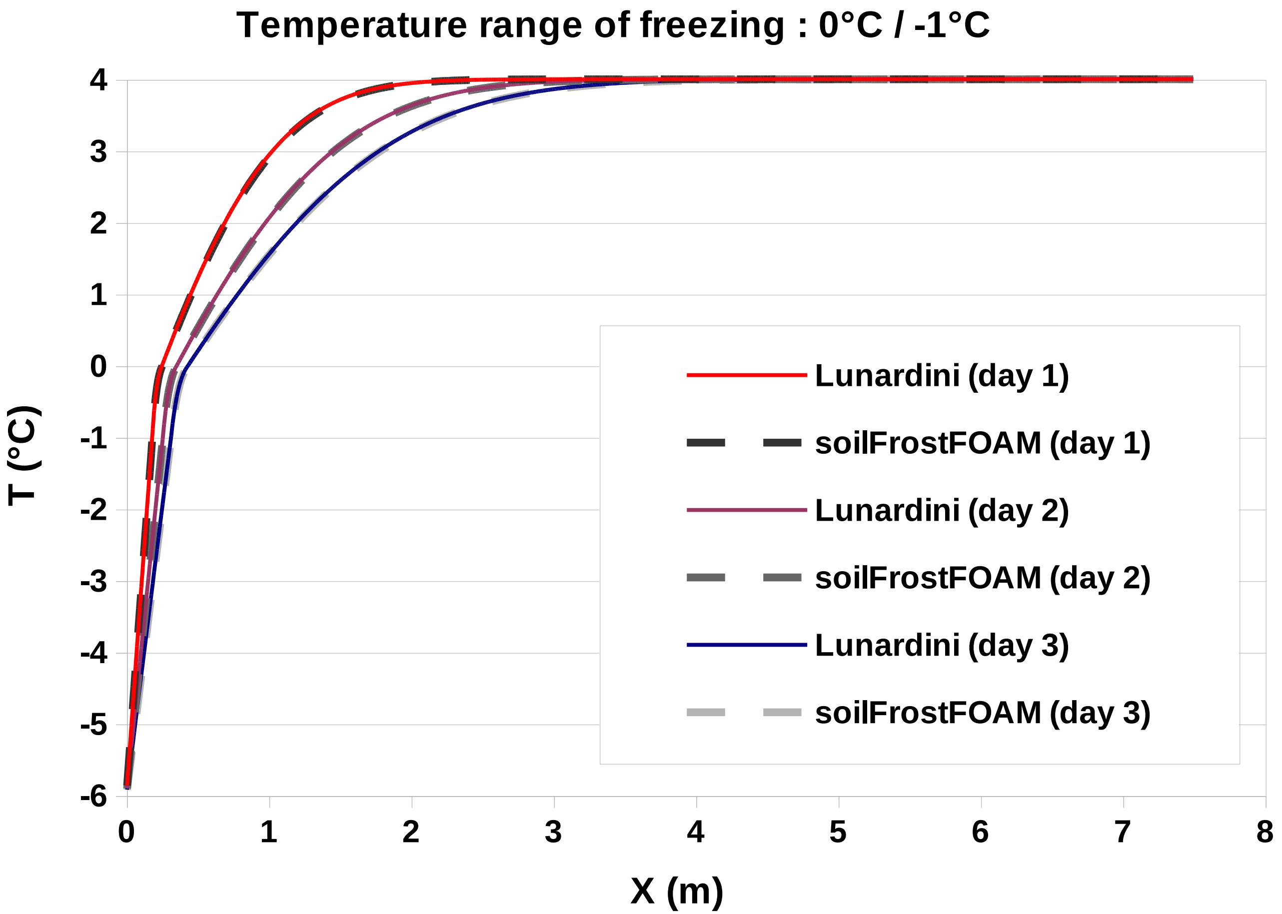
Exection time : ~ 1 s
(Intel® Core™ i7-2760QM CPU @ 2.40GHz × 8)

Dt0 = 1e-2 s Dtmax = 1 h

Tfact = 1.3

DIC-PCG precision : 1e-6 m
Picard precison : 1e-4 m

The purely conductive Lunardini case: 1D transient analytical solution for thermal transfer / phase changes



Error max (T, °C) : <0.05

Mesh cell size : 1e-2 m (750 cells)

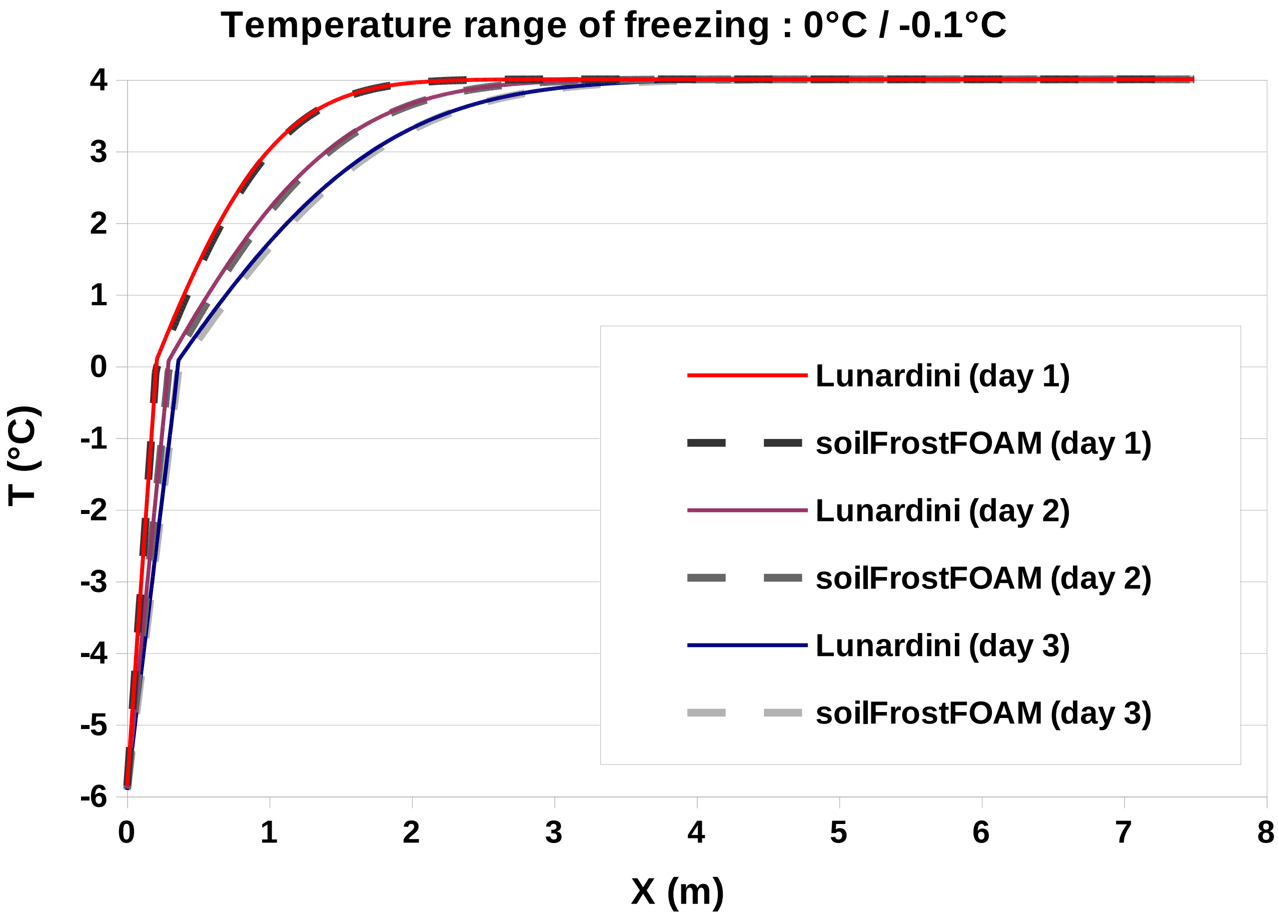
Exection time : ~ 2 s
(Intel® Core™ i7-2760QM CPU @ 2.40GHz × 8)

Dt0 = 0.5 s Dtmax = 15 mn

Tfact = 1.3

DIC-PCG precision : 1e-6 m
Picard precison : 1e-3 m

The purely conductive Lunardini case:
1D transient analytical solution for thermal transfer / phase changes



Temperature range of freezing : 0°C / -0.1°C

Error max (T, °C) : <0.15

Mesh cell size : 1e-2 m (750 cells)

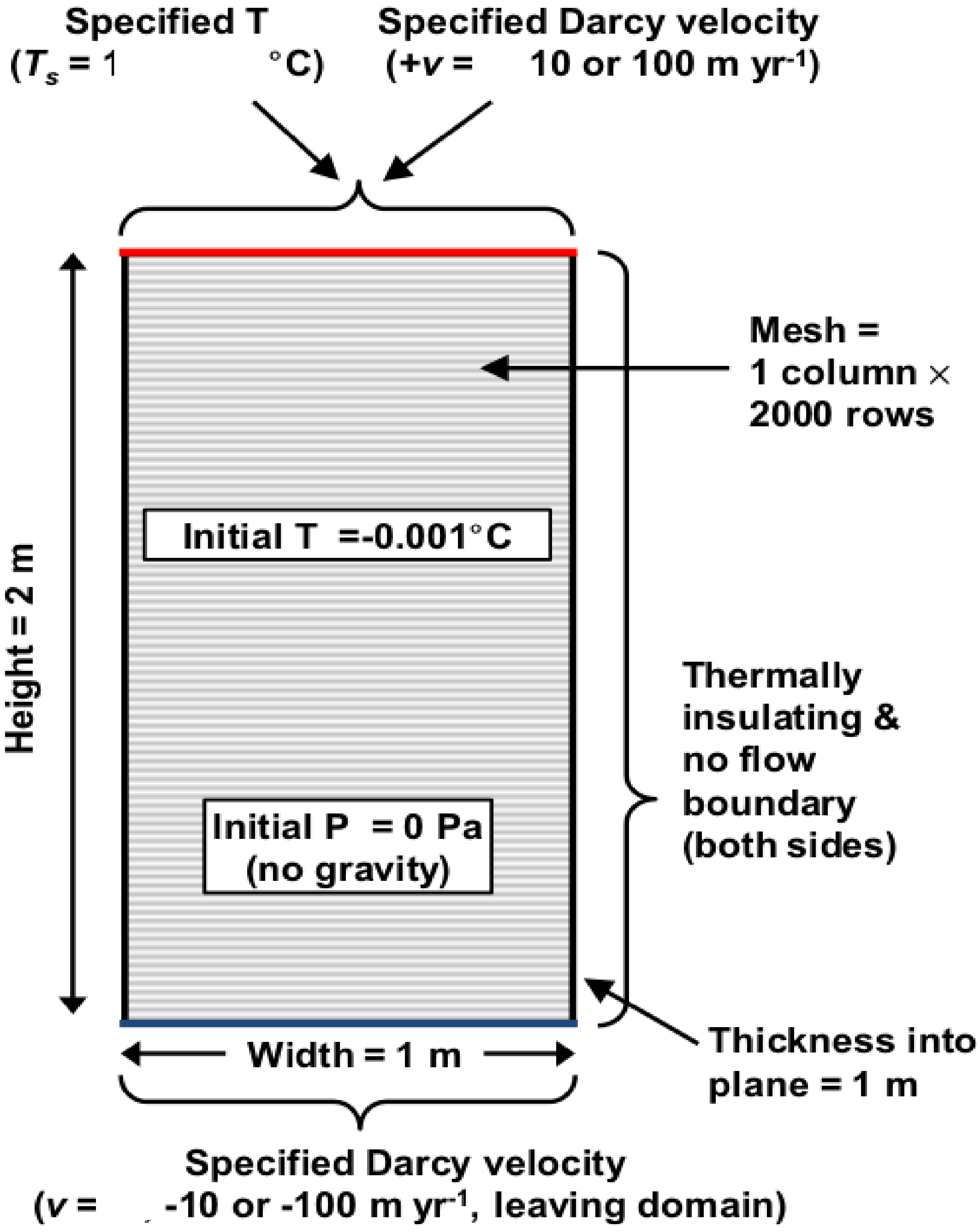
Exection time : ~ 28 mn
(Intel® Core™ i7-2760QM CPU @ 2.40GHz × 8)

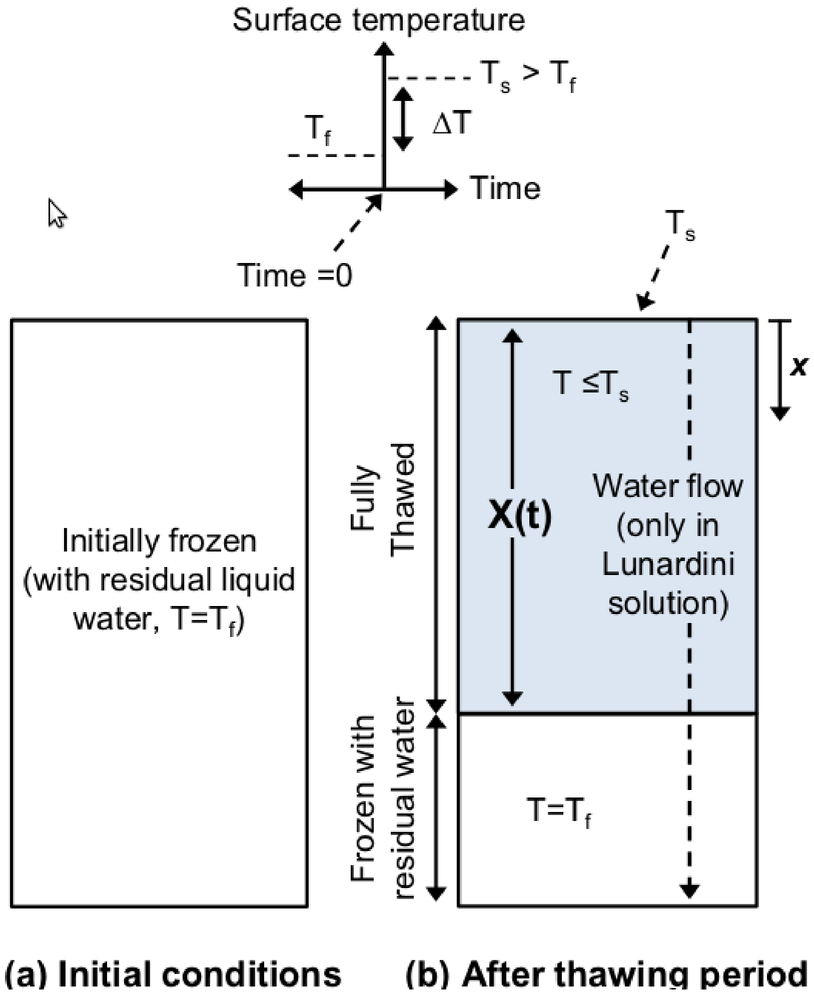
Dt0 =1e-7 s Dtmax = 10 s

Tfact = 1.5

DIC-PCG precision : 1e-8 m
Picard precison : 1e-6 m

The advective-conductive Lunardini case, Kurylyk et al. 2014
1D transient analytical solution for thermal transfer / phase changes





(Figures extracted from Kurylyk et al. 2014)

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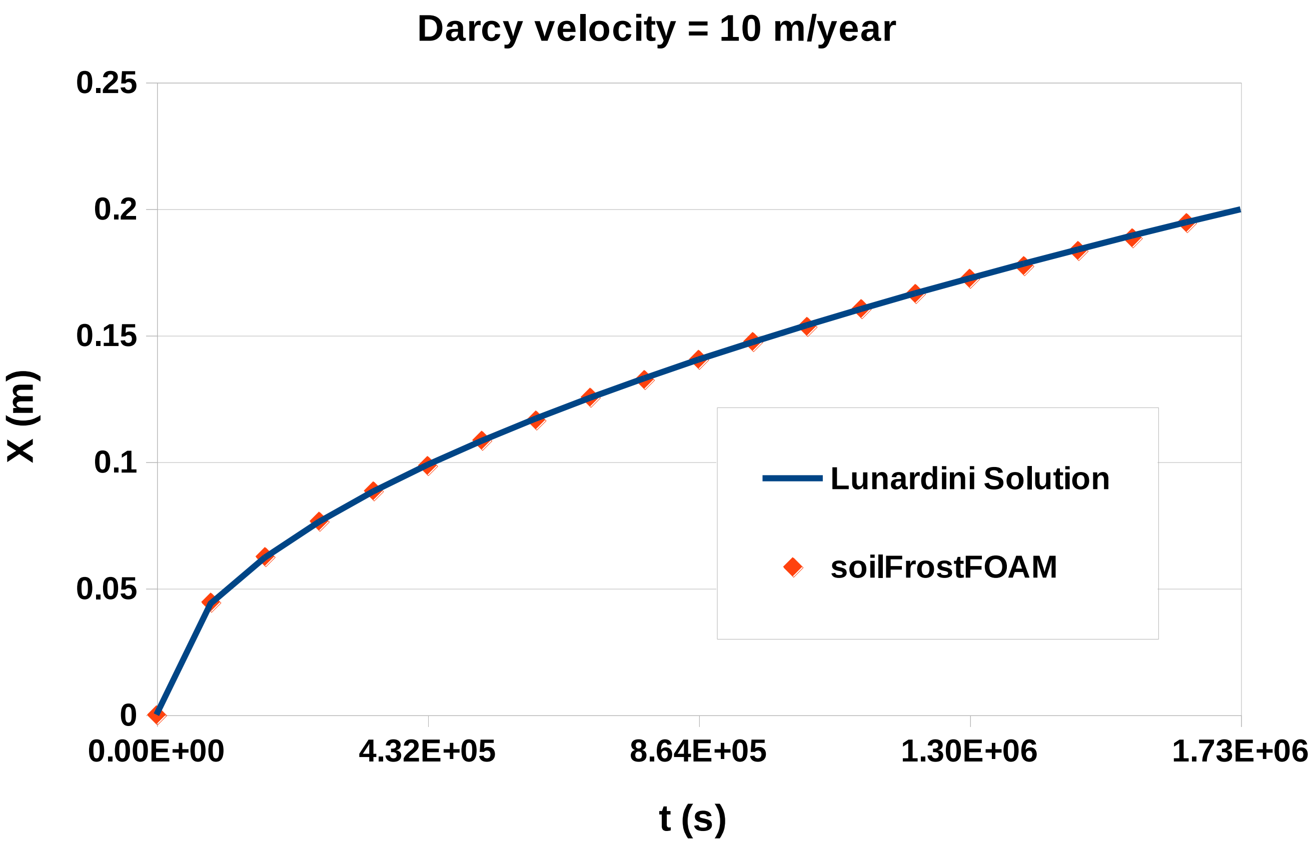
T temperature [K], T_f starting temperature of water freezing [K], T_m starting temperature of ice melting [K], with T_f and T_m very close from each other ($T_f - T_m = 0.0005$), t time [s], C_n volumetric heat capacity [kg.m.s^{-3}.K^{-1}] of zone n, C_n volumetric heat capacity [kg.m.s^{-3}.K^{-1}] of water, v Darcy velocity of water flow [m.s-1], K_n thermal conductivity [kg.m.s^{-3}.K^{-1}] of zone n, L latent heat of fusion of ice [kg.m^{-1}.s^{-2}], θ_{liquid} volumetric fraction of liquid water [-], θ_{ice} volumetric fraction of ice [-], θ_s saturated volumetric fraction of liquid water [-], θ_r residual volumetric fraction of liquid water [-].

The advective-conductive Lunardini case:
1D transient analytical solution for thermal transfer / phase changes



Max rel. error (%) : < 1.4

Mesh cell size : 1e-3 m (2000 cells)

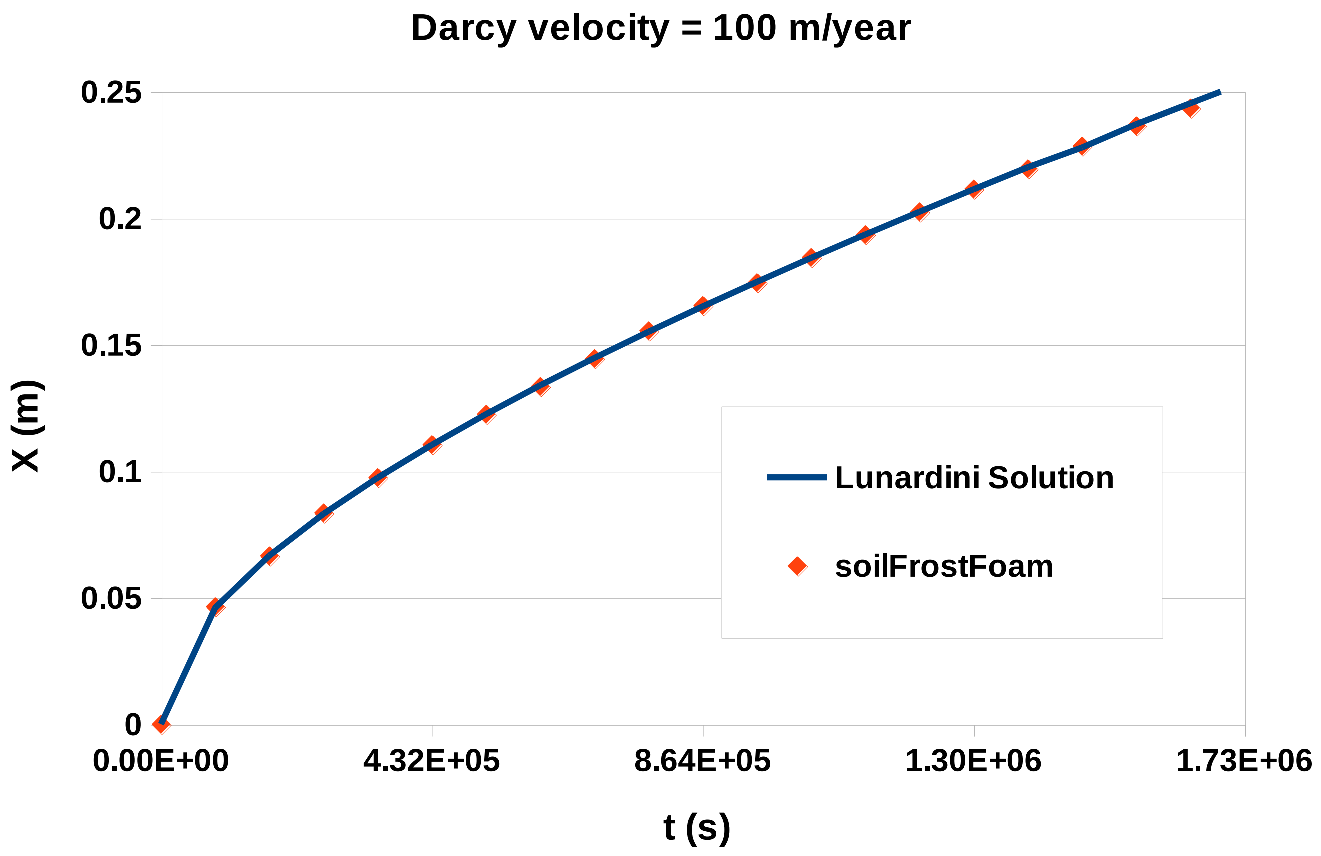
Exection time : ~ 63 s
(Intel® Core™ i7-2760QM CPU @ 2.40GHz × 8)

Dt0 =1e-5 s Dtmax = 100 s

Tfact = 1.1

DILU-PBiCG precision : 1e-8 m
Picard precison : 1e-6 m

The advective-conductive Lunardini case: 1D transient analytical solution for thermal transfer / phase changes



Max rel. error (%) : < 1.1

Mesh cell size : 1e-3 m (2000 cells)

Exection time : ~ 63 s
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Dt0 =1e-5 s Dtmax = 100 s

Tfact = 1.1

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Picard precison : 1e-6 m

Conclusions

A validated implementation for advective-conductive thermal transport with phase change in porous medium has been set up in the framework of OpenFOAM®.

OpenFOAM solver: directly 3D, parallel

Perspectives :

coupling with RichardsFOAM (Orgogozo et al., CPC 2014)

Next steps of INTERFROST benchmark

Application to field data sets

Study of the parallel performances

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Thank you for your attention.

Contact : laurent.orgogozo@get.obs-mip.fr