Detailed presentation of test cases

C. Grenier, B. Kurylyk

Coupled TH model, Cast3M code: … where we want to end up

– Heat transfer

$$\left(\rho_w S_w C_w \epsilon + \rho_i S_i C_i \epsilon + (1-\epsilon)\rho_s C_s + \epsilon \rho_i L \frac{\partial S_i}{\partial T}\right)\frac{\partial T}{\partial t} = \nabla.(\lambda_t \nabla T) + \nabla.\left[\rho_w c_w T.\vec{\nabla} p + \rho_w c_w T.\vec{\nabla} z\right]$$

– Water transfer

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

Program: from simple to complex !

- T1 – T3: purely thermal, 1D
- T->P: pressure increases with freezing
- TH1: advective term
- TH2, TH3: coupled cases

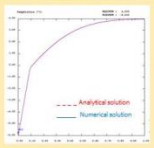
Overview

1D Thermal with advective component

T1: Lunardini/Osterkamp

Analytical solution:

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



Temperature profiles (Cast3M code vs Lunardini solution)

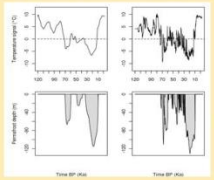
T2: Heterogeneous

Multi-layered, bounded, with geothermal flux.

Include field monitoring data.

T3: geological times

Heterogeneous, with geothermal flux, long simulation times



After Régnier, 2012

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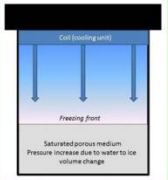

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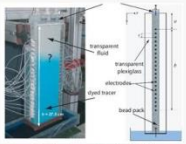

Lekmine et al. 2011

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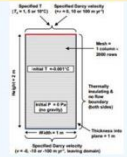

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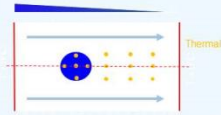

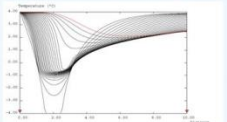

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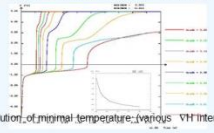

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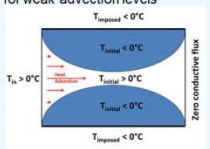

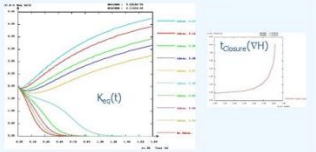

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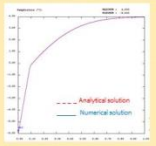

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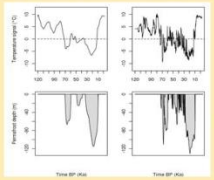

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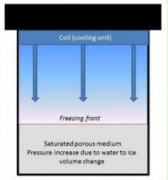

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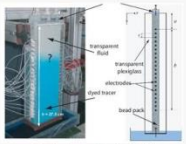

Lekmine et al. 2011

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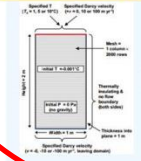

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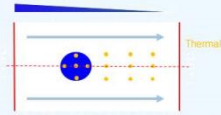

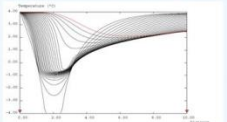

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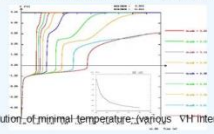

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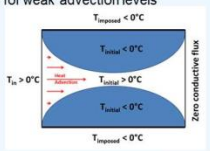

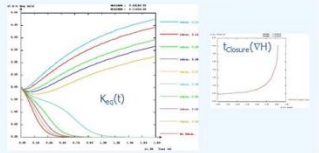

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- B. Kurylyk & J. McKenzie

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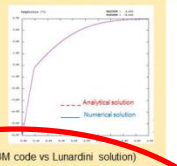

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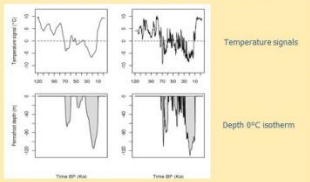

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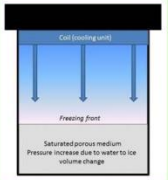

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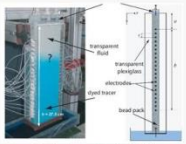

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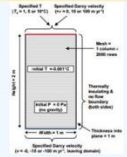

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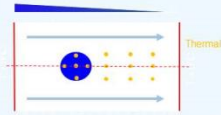

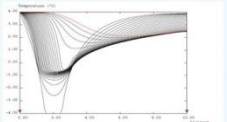

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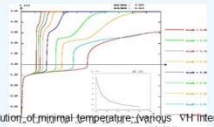

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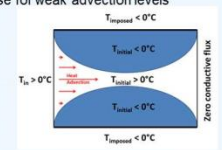

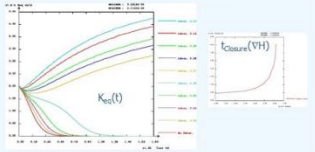

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Pure T: T2 and T3

- Bounded system, heterogeneity, geothermal flux
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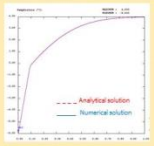

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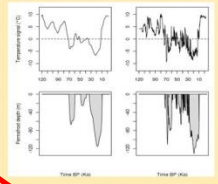

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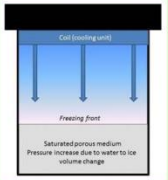

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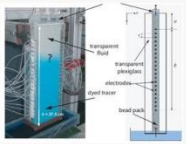

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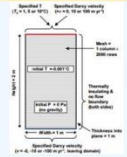

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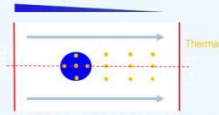

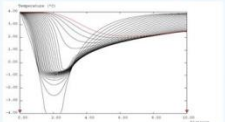

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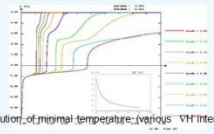
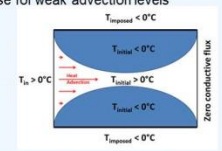


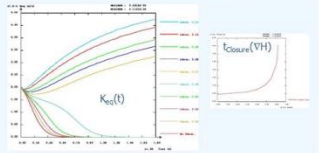
Evolution of minimal temperature (various ∇H intensities)

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





1D Thermal

1D Thermal with impact on pressure (no motion)

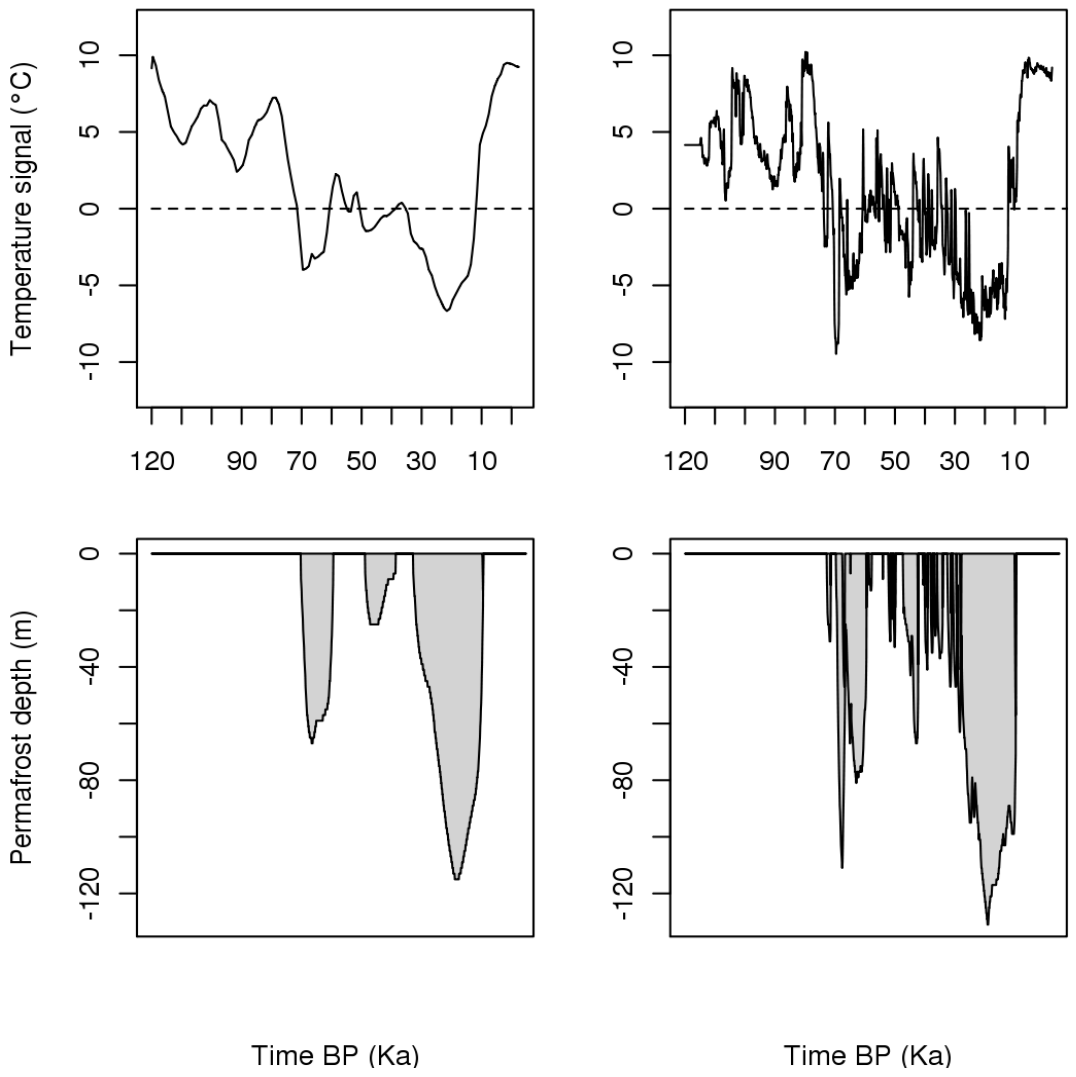
2D with full TH coupling

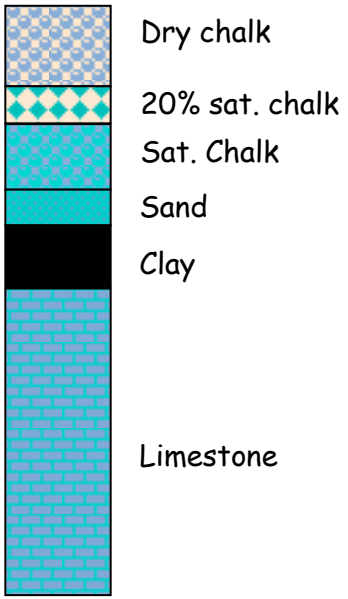
T3: long time evolution of permafrost depth

Temperature

0°C Isotherm depth evolution

Signal with rapid variability





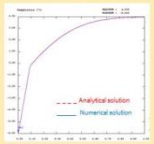
Overview

1D Thermal with advective component

T1: Lunardini/Osterkamp

Analytical solution:

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



Temperature profiles (Cast3M code vs Lunardini solution)

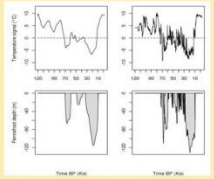
T2: Heterogeneous

Multi-layered, bounded, with geothermal flux.

Include field monitoring data.

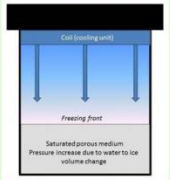
T3: geological times

Heterogeneous, with geothermal flux, long simulation times

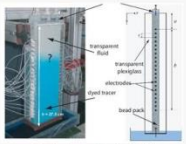


After Régnier, 2012

T→P: 1D P↑



Experiments in cold room



Lekmine et al. 2011

Facility at GEOPS with controlled room temperature

Coupled system of TH equations

Darcy water flow equation

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

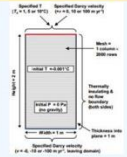
Heat transfer equation

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

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

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)

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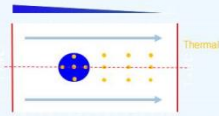
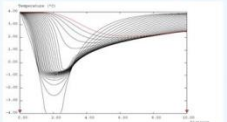
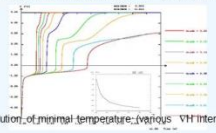




Longitudinal temperature profiles (Cast3M code)



Evolution of minimal temperature (various ∇H intensities)

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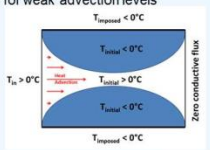
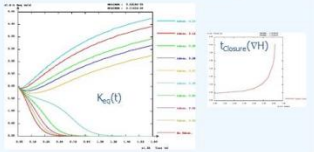




1D Thermal

1D Thermal with impact on pressure (no motion)

2D with full TH coupling

InterFrost Test Case T->P

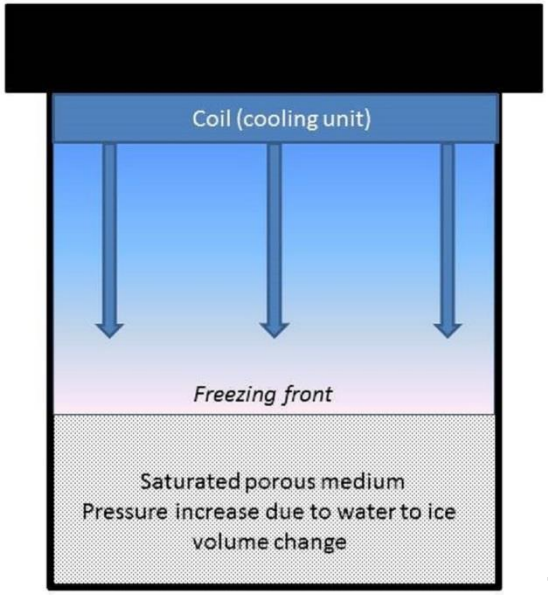
$$\left(\rho_w S_w C_w \epsilon + \rho_i S_i C_i \epsilon + (1-\epsilon)\rho_s C_s + \epsilon \rho_i L \frac{\partial S_i}{\partial T}\right)\frac{\partial T}{\partial t} = \nabla.(\lambda_t \nabla T) + \nabla.\left[\rho_w c_w T.\vec{\nabla} p + \rho_w c_w T.\vec{\nabla} z\right]$$

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

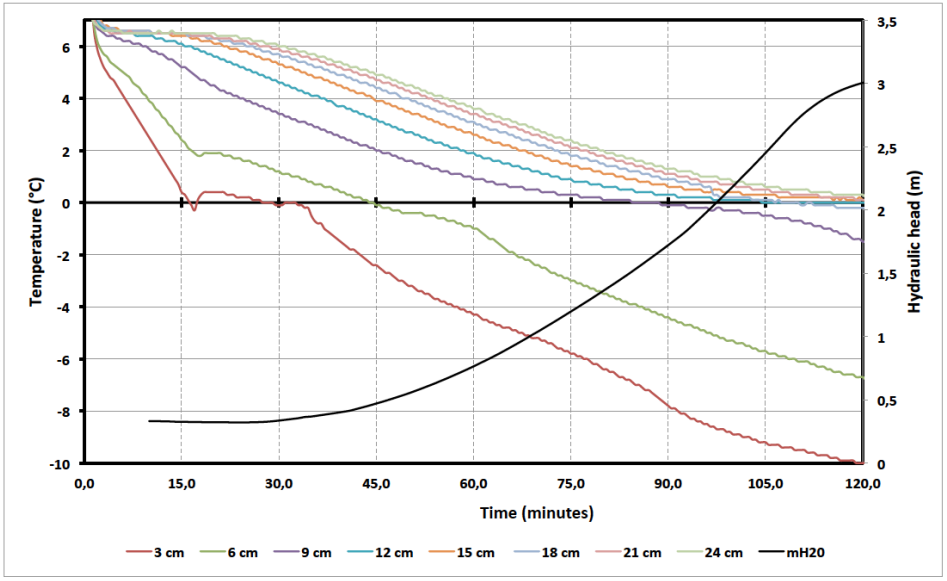
Pressure increase due to water freezing.

No fluid movement, constant volume

(intended for code validation, not real world)



Monitoring of temperature (vertical profile) and water pressure in the unfrozen porous media



« controlled conditions »?

Side losses (minimized by insulation & cold room conditions)

Total volume constant? (upper surface topography monitoring)

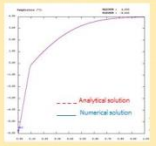
Overview

1D Thermal with advective component

T1: Lunardini/Osterkamp

Analytical solution:

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



Temperature profiles (Cast3M code vs Lunardini solution)

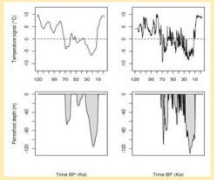
T2: Heterogeneous

Multi-layered, bounded, with geothermal flux.

Include field monitoring data.

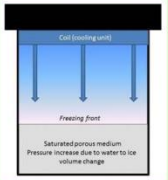
T3: geological times

Heterogeneous, with geothermal flux, long simulation times

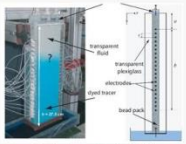


After Régnier, 2012

T→P: 1D P↑



Experiments in cold room



Lekmine et al. 2011

Facility at GEOPS with controlled room temperature

Coupled system of TH equations

Darcy water flow equation

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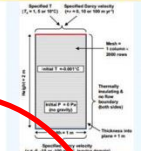
TH1: Kurylyk & Lunardini



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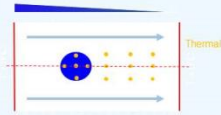
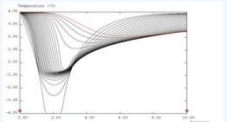
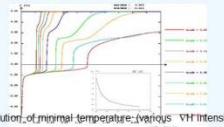




Longitudinal temperature profiles (Cast3M code)



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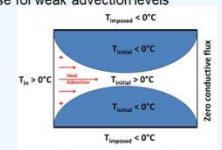
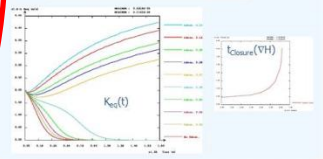




1D Thermal

1D Thermal with impact on pressure (no motion)

2D with full TH coupling

Coupled TH model, TH2: Frozen Inclusion

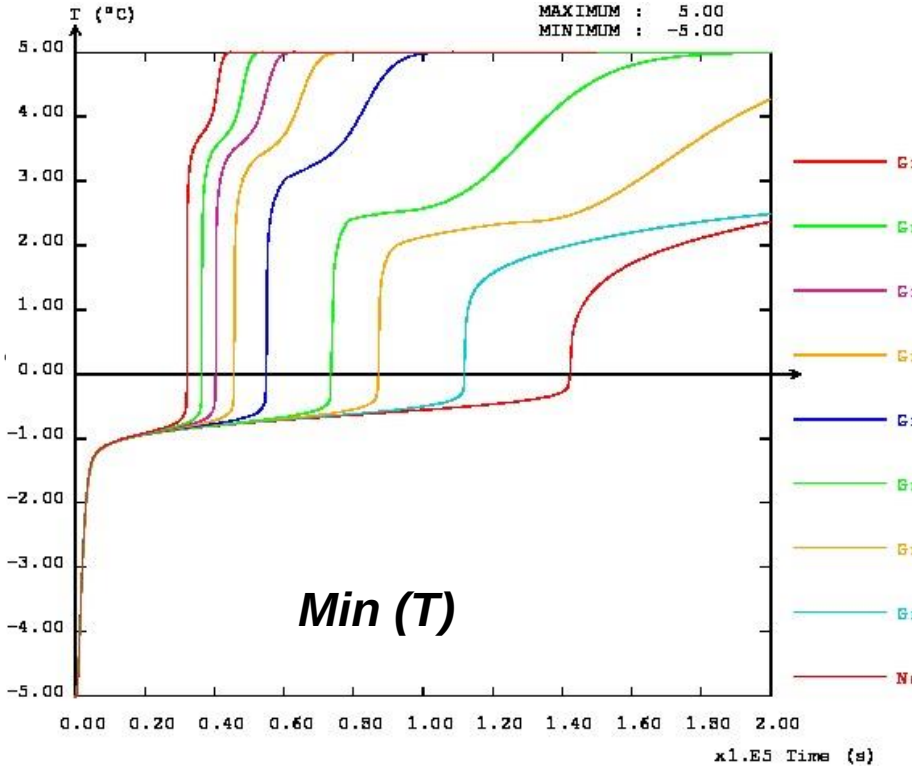
- Sensitivity to water flow rates
  - Heat transfer

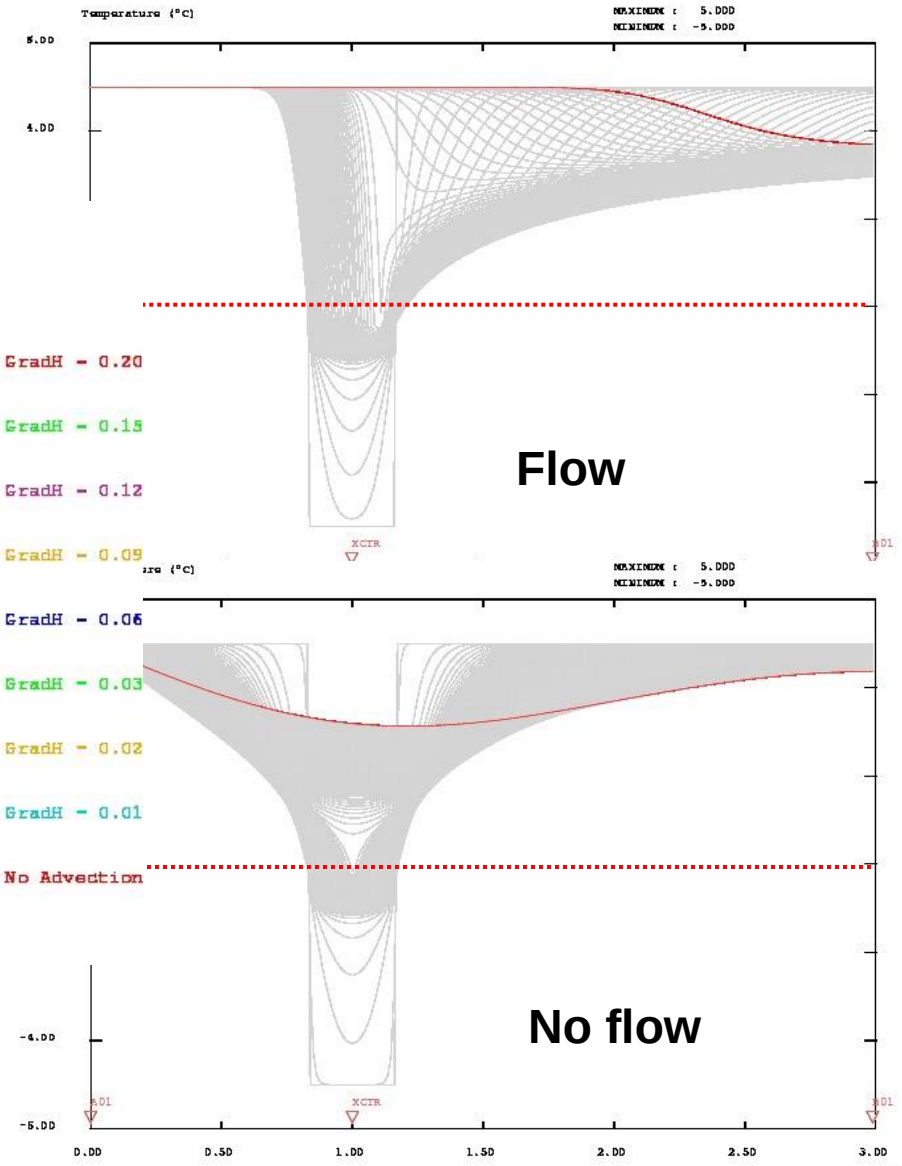
$$\left(\rho_w S_w C_w \epsilon + \rho_i S_i C_i \epsilon + (1-\epsilon)\rho_s C_s + \epsilon \rho_i L \frac{\partial S_i}{\partial T}\right)\frac{\partial T}{\partial t} = \nabla.(\lambda_t \nabla T) + \nabla.\left[\rho_w c_w T.\vec{\nabla} p + \rho_w c_w T.\vec{\nabla} z\right]$$

  - Water transfer

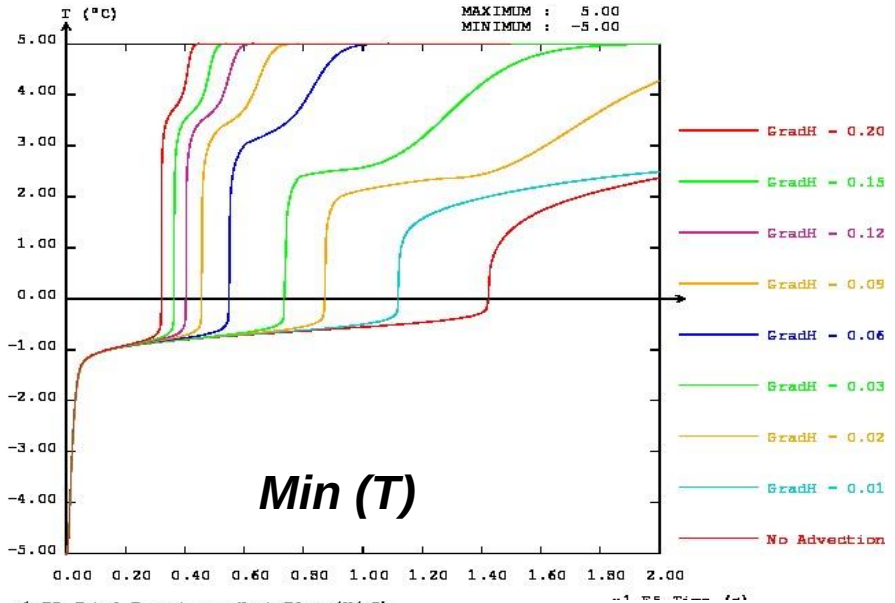
$$\left(S_w \frac{\partial \epsilon \rho_w}{\partial \rho}\right)\frac{\partial p}{\partial t} = \nabla.\left[\rho_w K_w \vec{\nabla} p\right] + \nabla.\left[\rho_w K_w \vec{\nabla} z\right] - \left(\epsilon(\rho_w - \rho_i)\frac{\partial S_w}{\partial T}\right)\frac{\partial T}{\partial t}$$

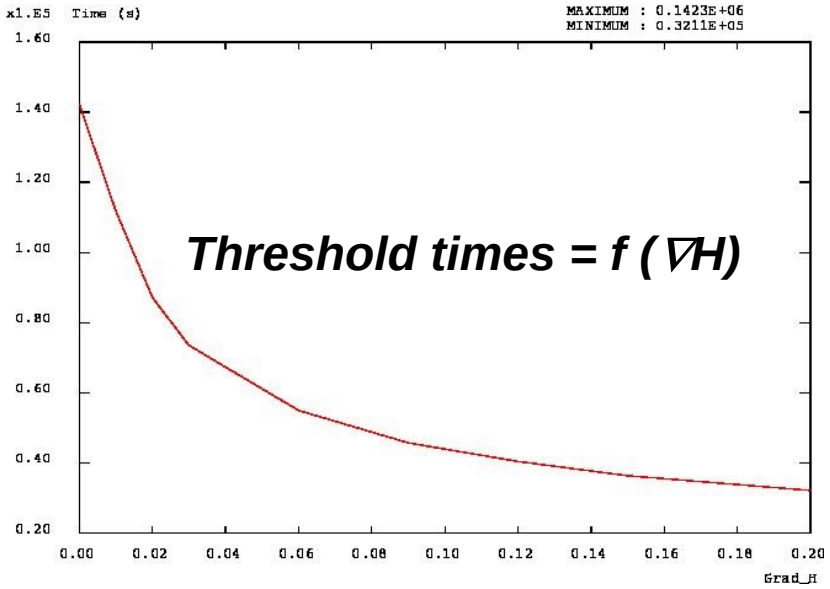
TH2

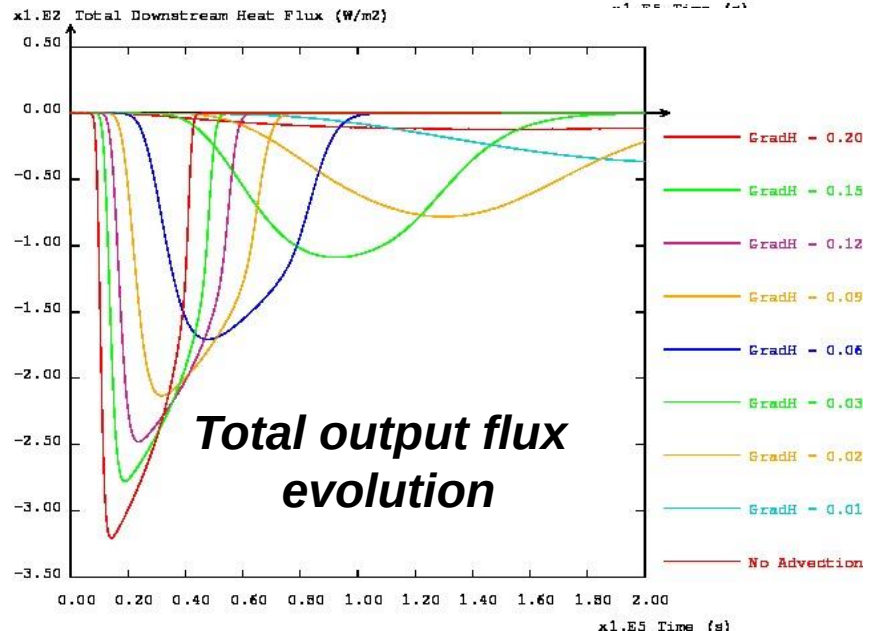

T (°C)
MAXIMUM : 5.00
MINIMUM : -5.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
0.00 0.20 0.40 0.60 0.80 1.00 1.20 1.40 1.60 1.80 2.00
x1.E5 Time (s)
GradH - 0.20
GradH - 0.15
GradH - 0.12
GradH - 0.09
GradH - 0.06
GradH - 0.03
GradH - 0.02
GradH - 0.01
No Advection
Min (T)

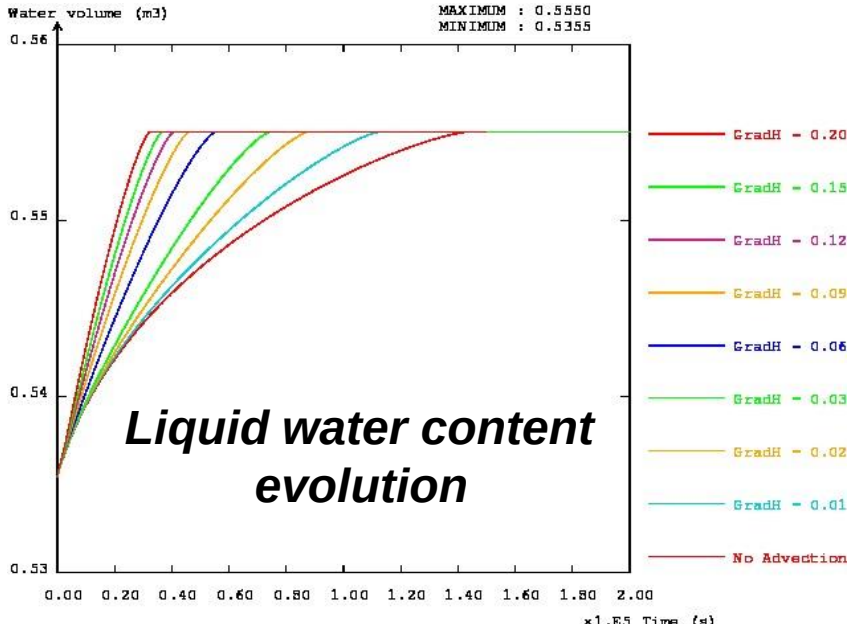

Temperature (°C)
MAXIMUM : 5.000
MINIMUM : -5.000
5.00
4.00
XCTR
Flow
-4.00
-5.00
0.00 0.50 1.00 1.50 2.00 2.50 3.00
Distance (m)
No flow

TH2, performance measures



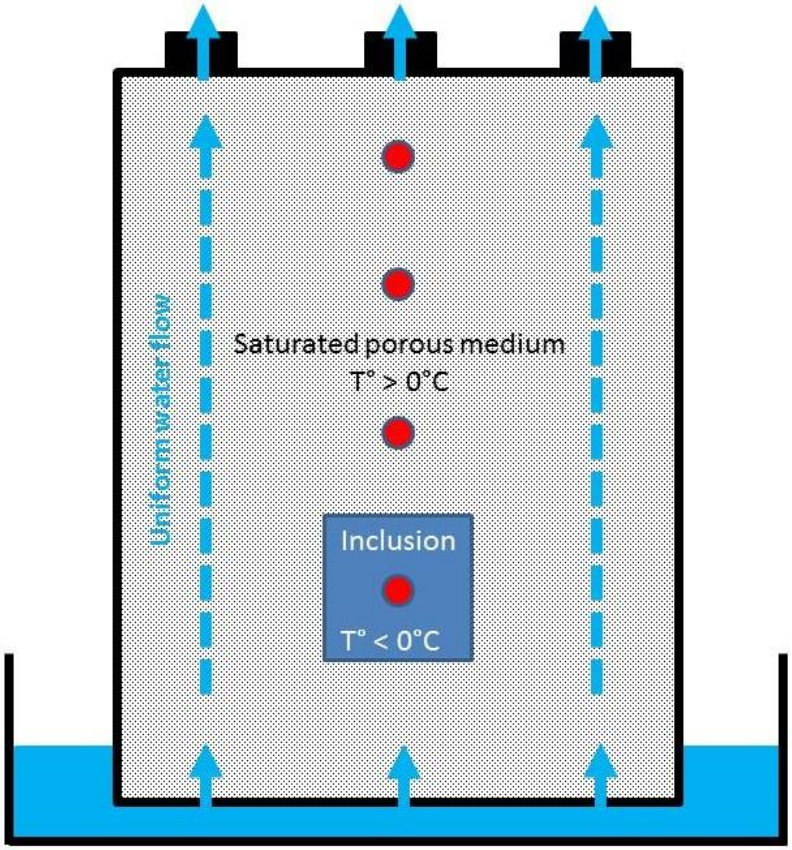






Lab. Experiment TH2 « Frozen Inclusion »

Monitoring of temperature (in the inclusion & downstream)
Monitoring of water flow rate
Measurement of transport velocity with tracer tests



« controlled conditions »?

Side heat losses (minimized with insulation & cold room conditions)
Initial conditions « smooth »
Control homogeneity of the porous medium (saturation & porosity)

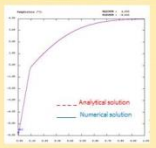
Overview

1D Thermal with advective component

T1: Lunardini/Osterkamp

Analytical solution:

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



Temperature profiles (Cast3M code vs Lunardini solution)

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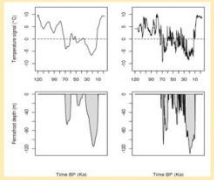
Multi-layered, bounded, with geothermal flux.

Include field monitoring data.

T3: geological times

Heterogeneous, with geothermal flux, long simulation times



After Régnier, 2012

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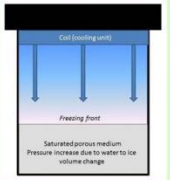
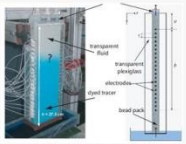


Experiments in cold room



Lekmine et al. 2011

Facility at GEOPS with controlled room temperature

Coupled system of TH equations

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Heat transfer equation

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

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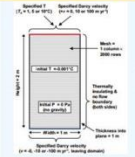

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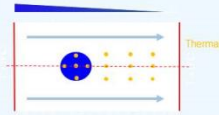

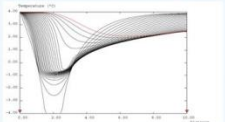

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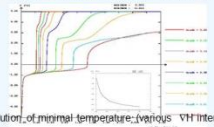

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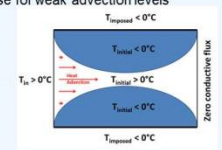
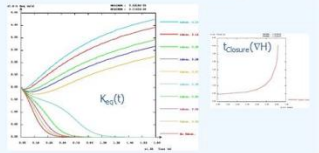




1D Thermal

1D Thermal with impact on pressure (no motion)

2D with full TH coupling

Experiments

- in cold room at GEOPS (Univ. Orsay)
- Visit tomorrow, chance to see them
- Still in a preliminary state

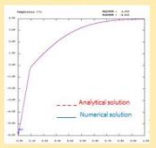
Overview

1D Thermal with advective component

T1: Lunardini/Osterkamp

Analytical solution:

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



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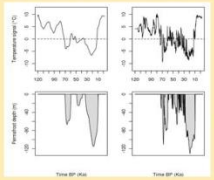

After Régnier, 2012

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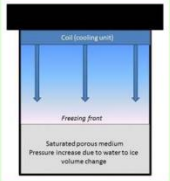

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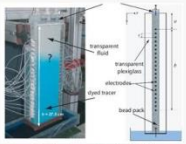

Lekmine et al. 2011

Facility at GEOPS with controlled room temperature

Coupled system of TH equations

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Heat transfer equation

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

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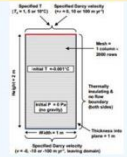

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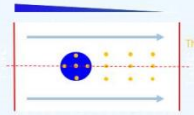

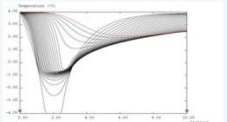

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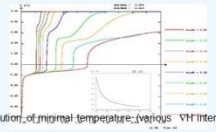

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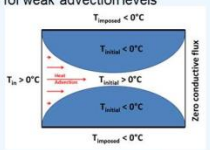

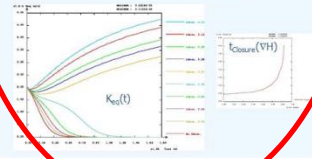

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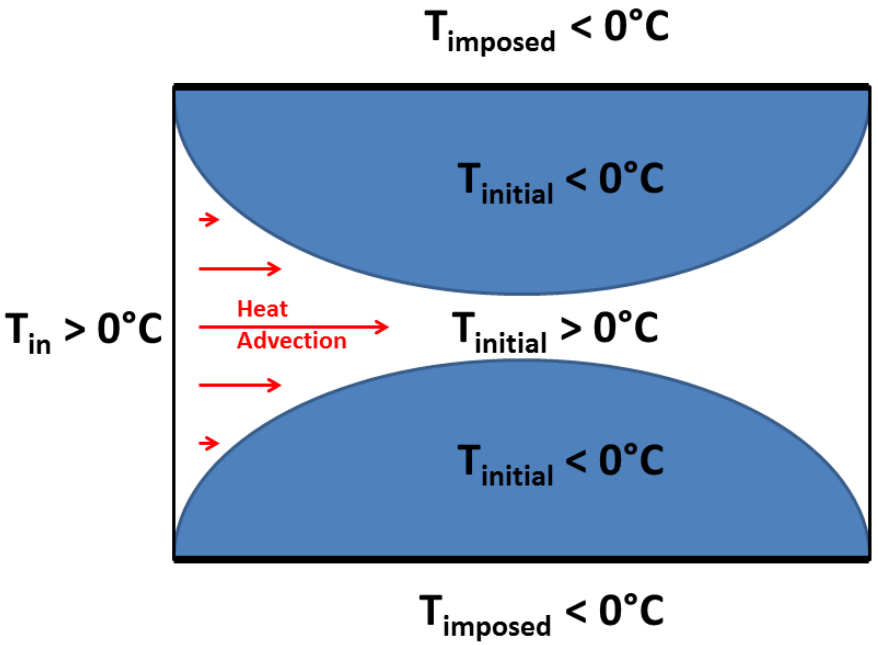
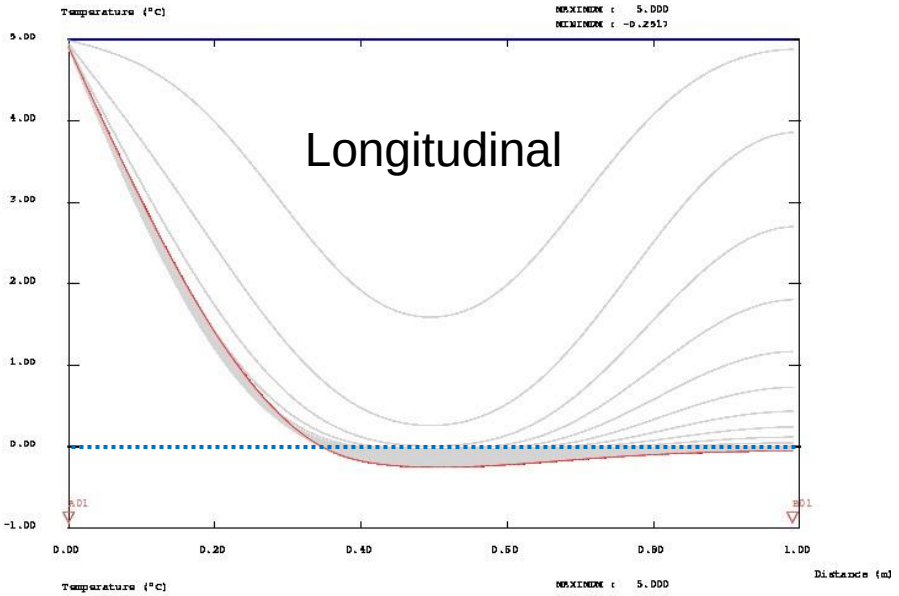
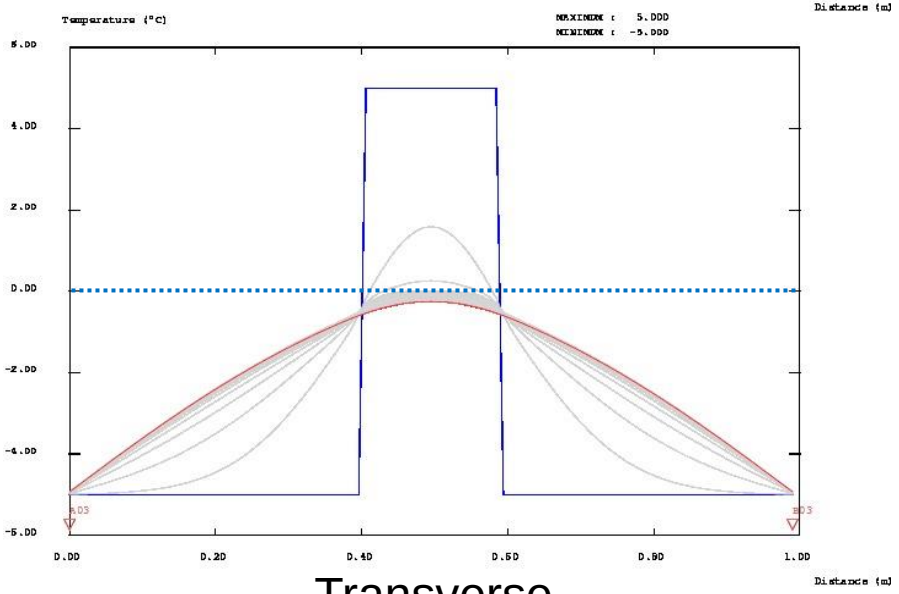


No flow

Zero conductive flux





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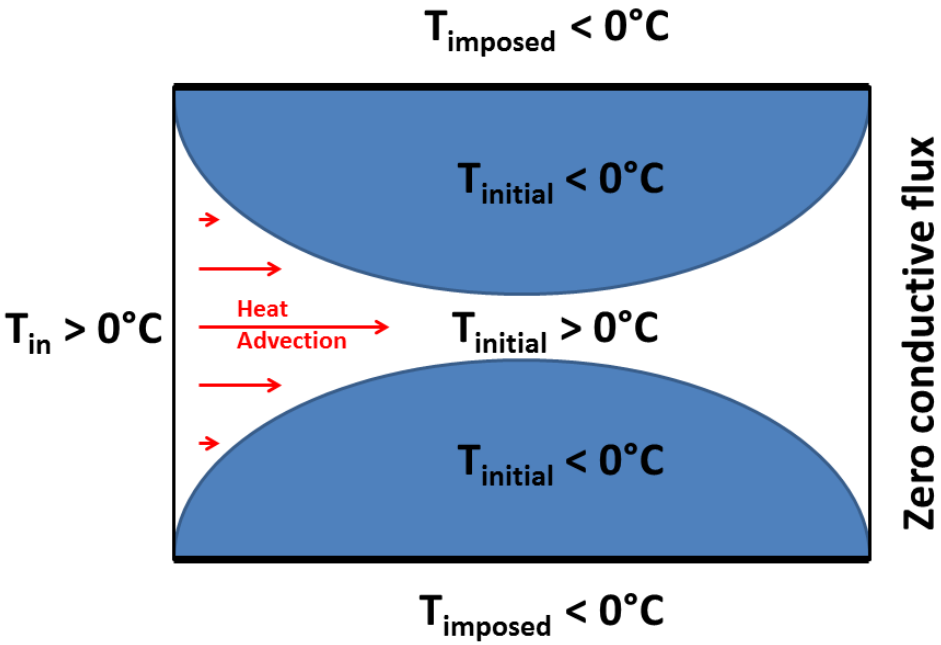

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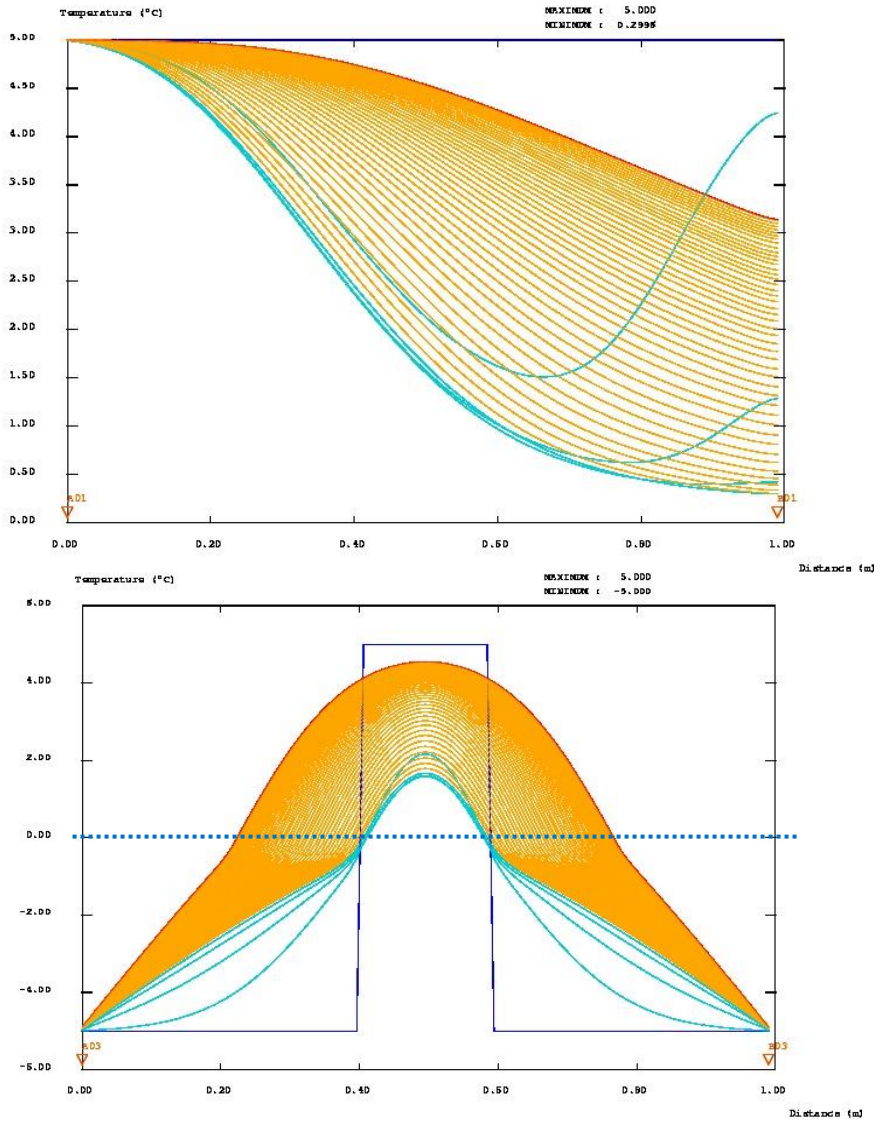

With flow

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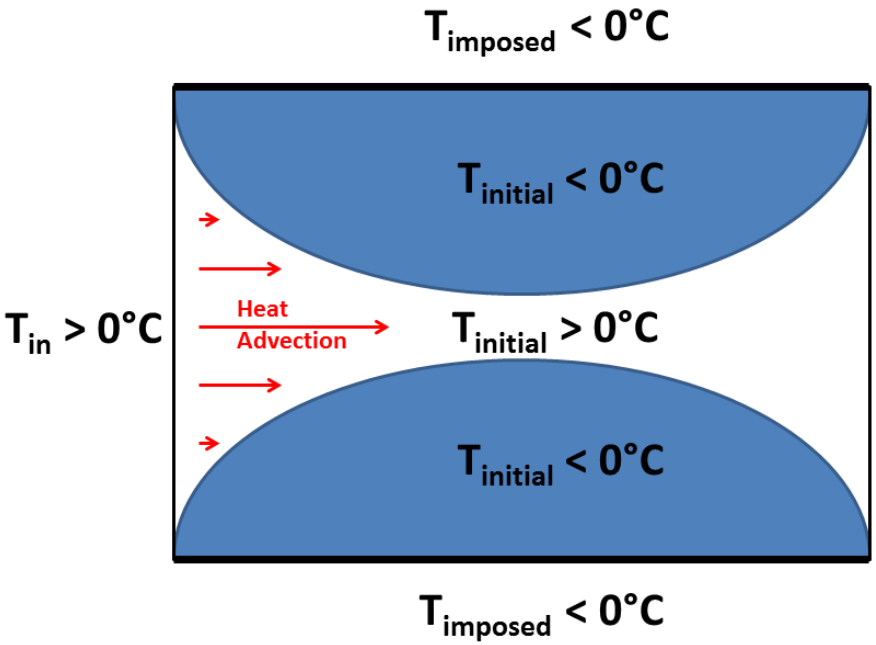

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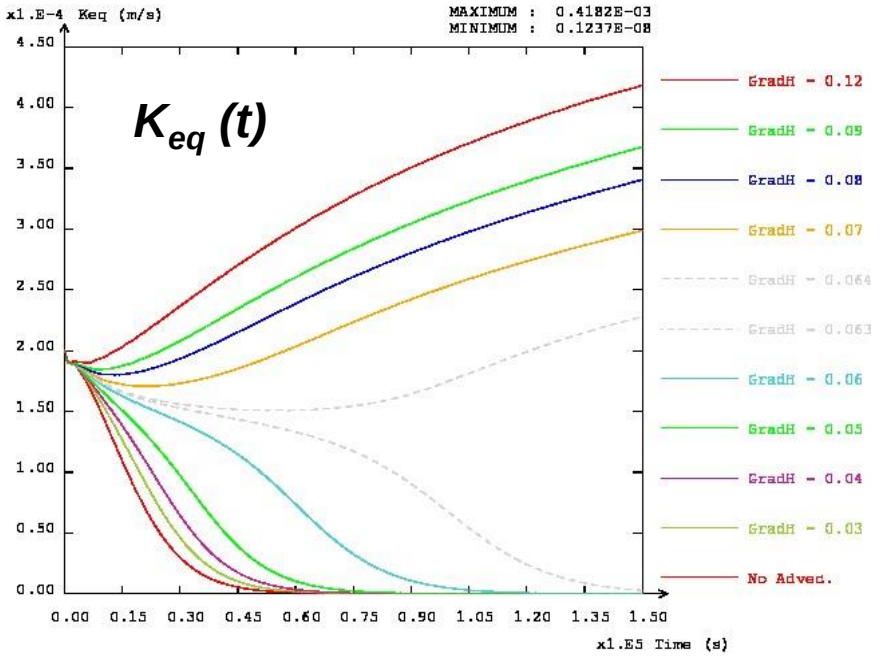
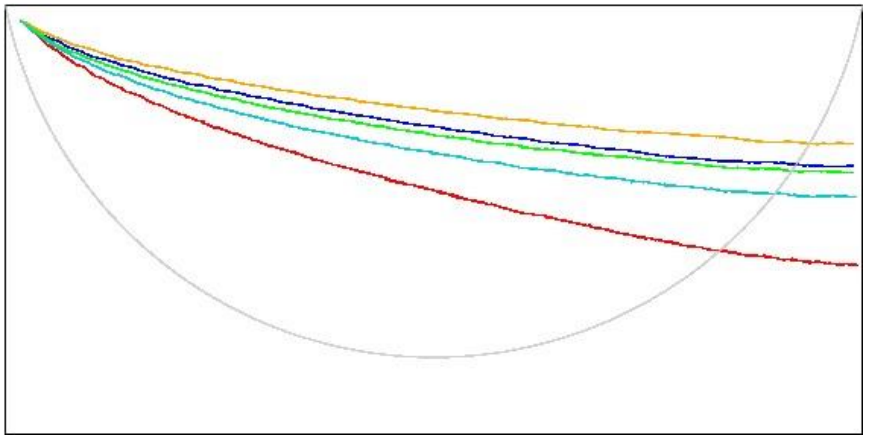
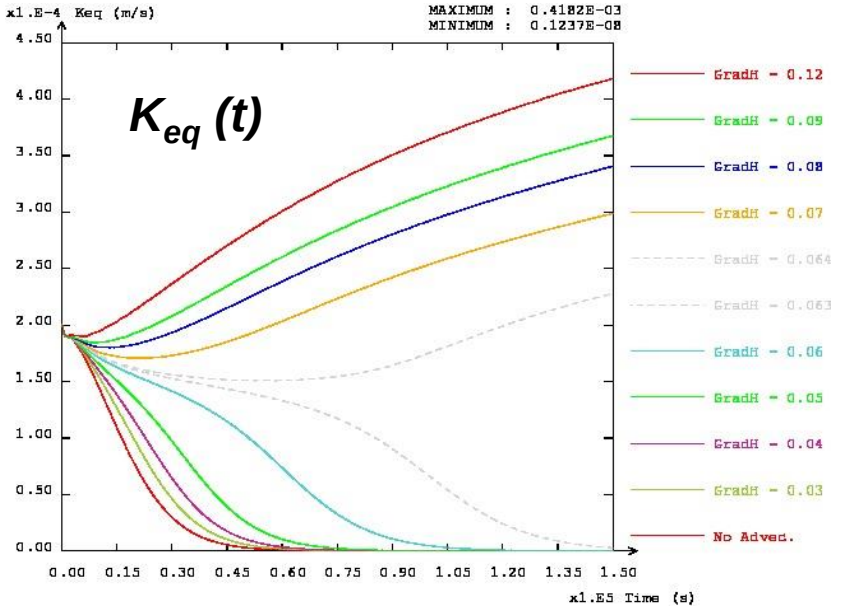
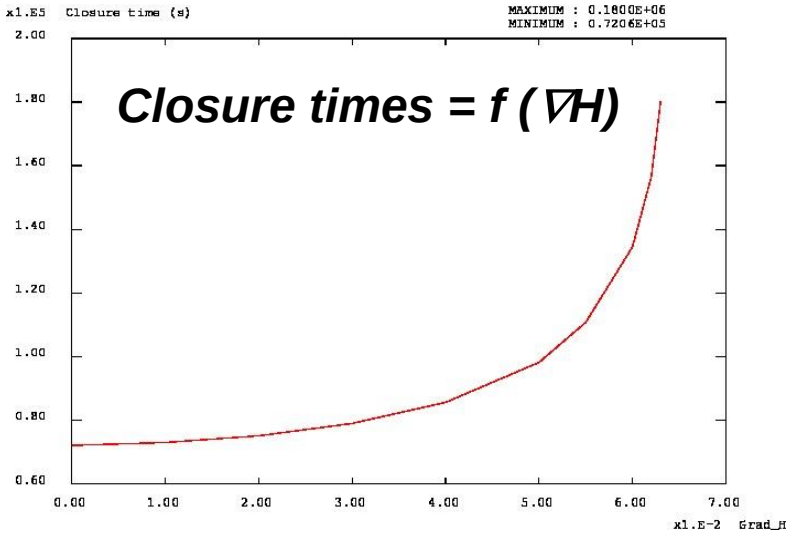


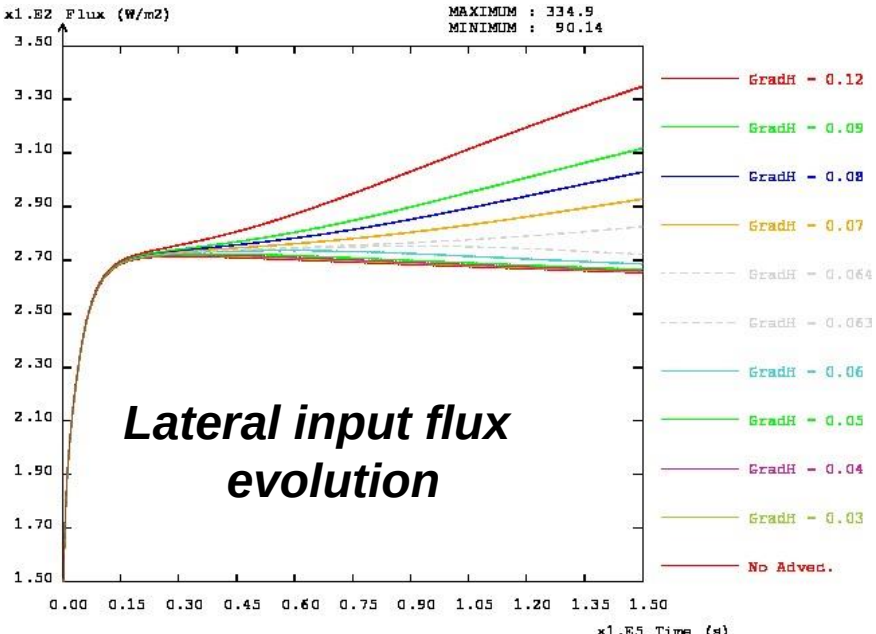


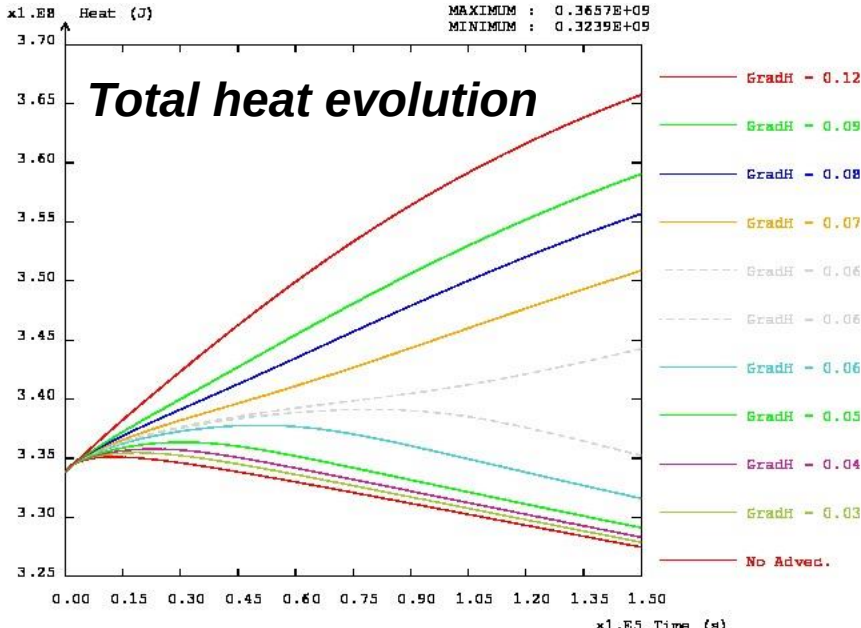
Steady state 0°C isotherm for opened talik

TH3, performance measures





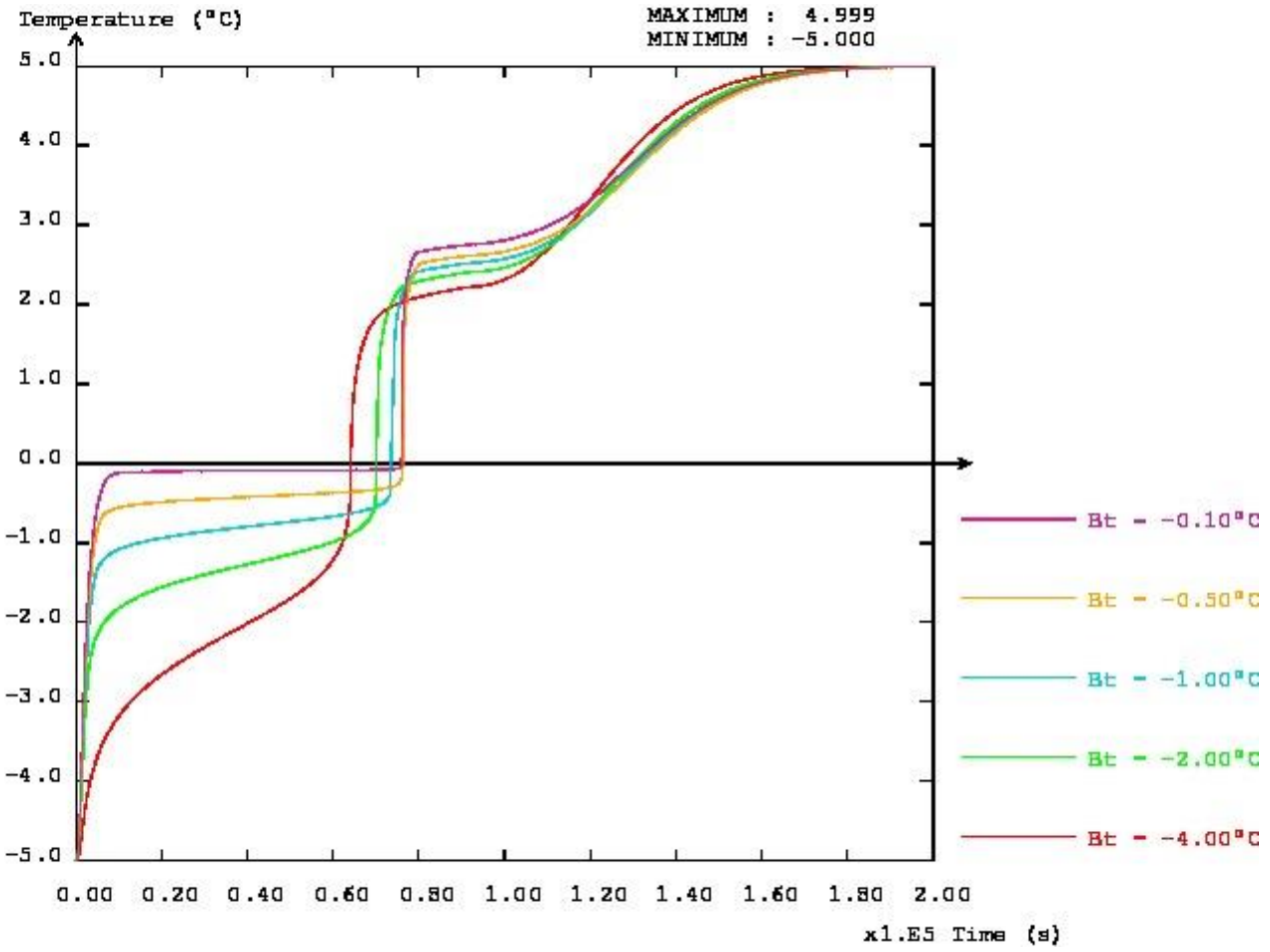




Convergence studies on TH2&3

- Simulations are converged
- What is the range of variation for the performance measures vor various discretisation strategies (spatial and temporal)? few percents
- Strong sensitivity to the liquid water saturation interval in the saturation curve!

Sensitivity to liquid water saturation interval for TH2



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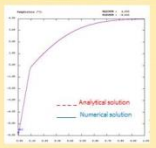

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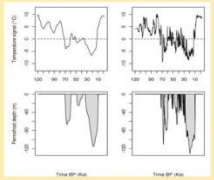

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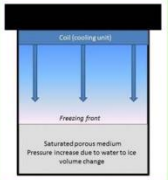

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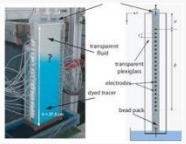

Lekmine et al. 2011

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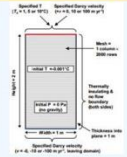

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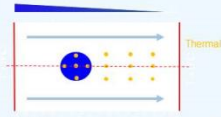

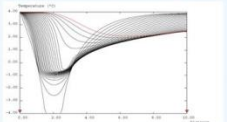

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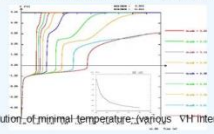

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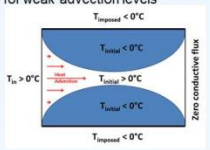

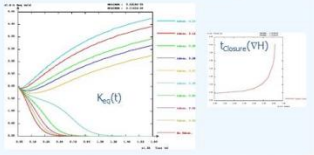

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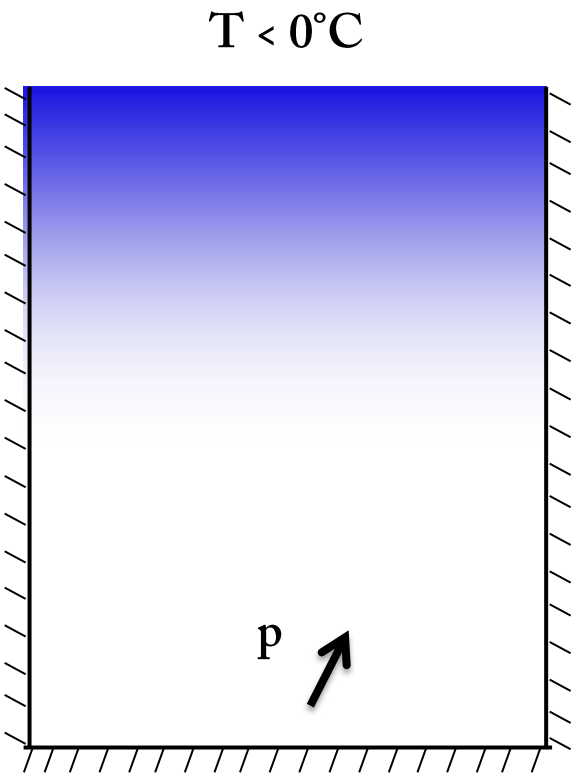
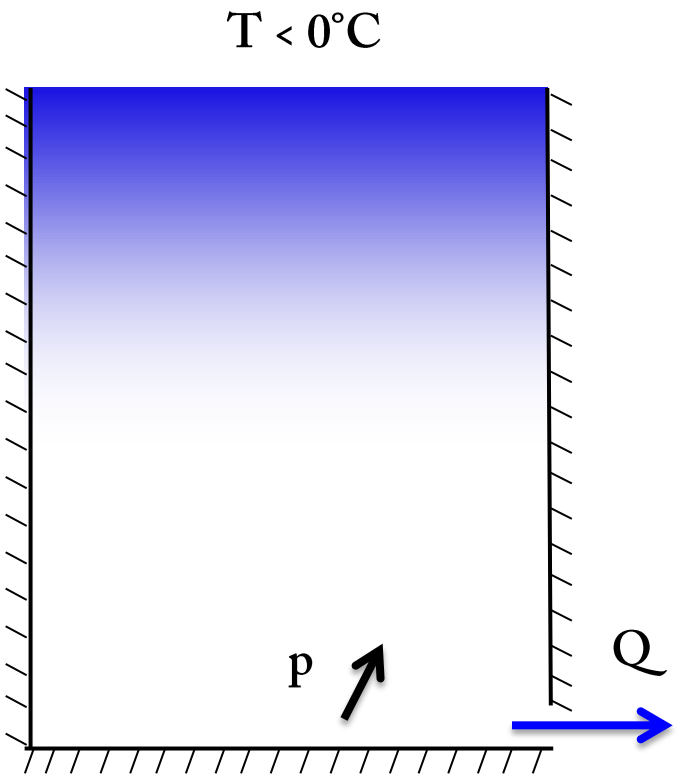
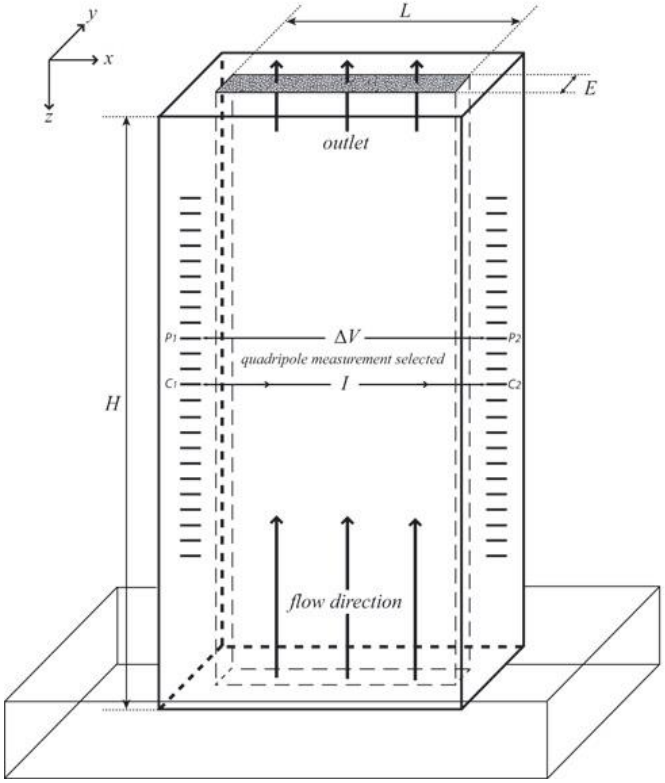
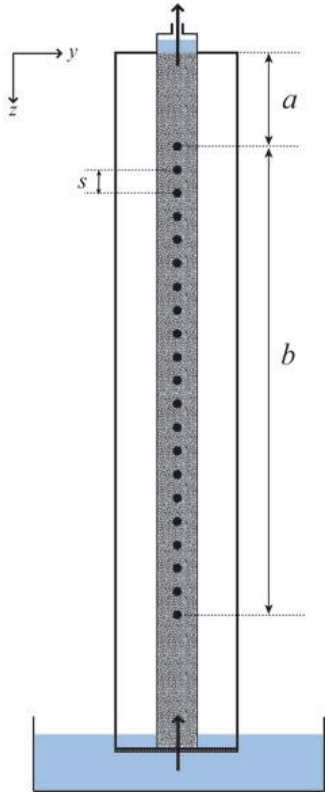
Pressure increase in confined layer (Task 2)

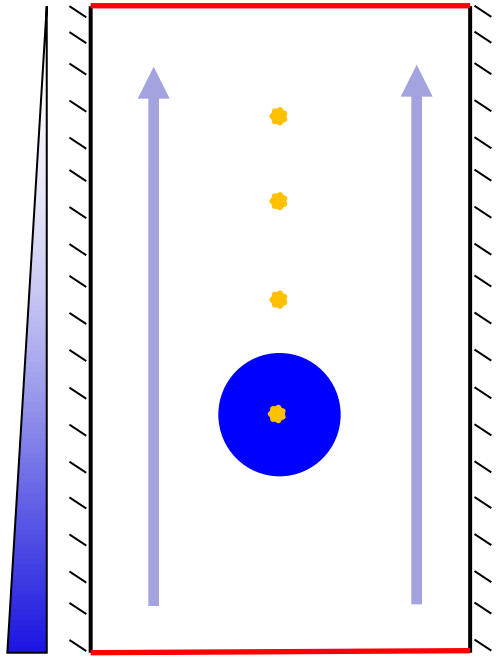




Associated cold room experiment at IDES, Paris Sud

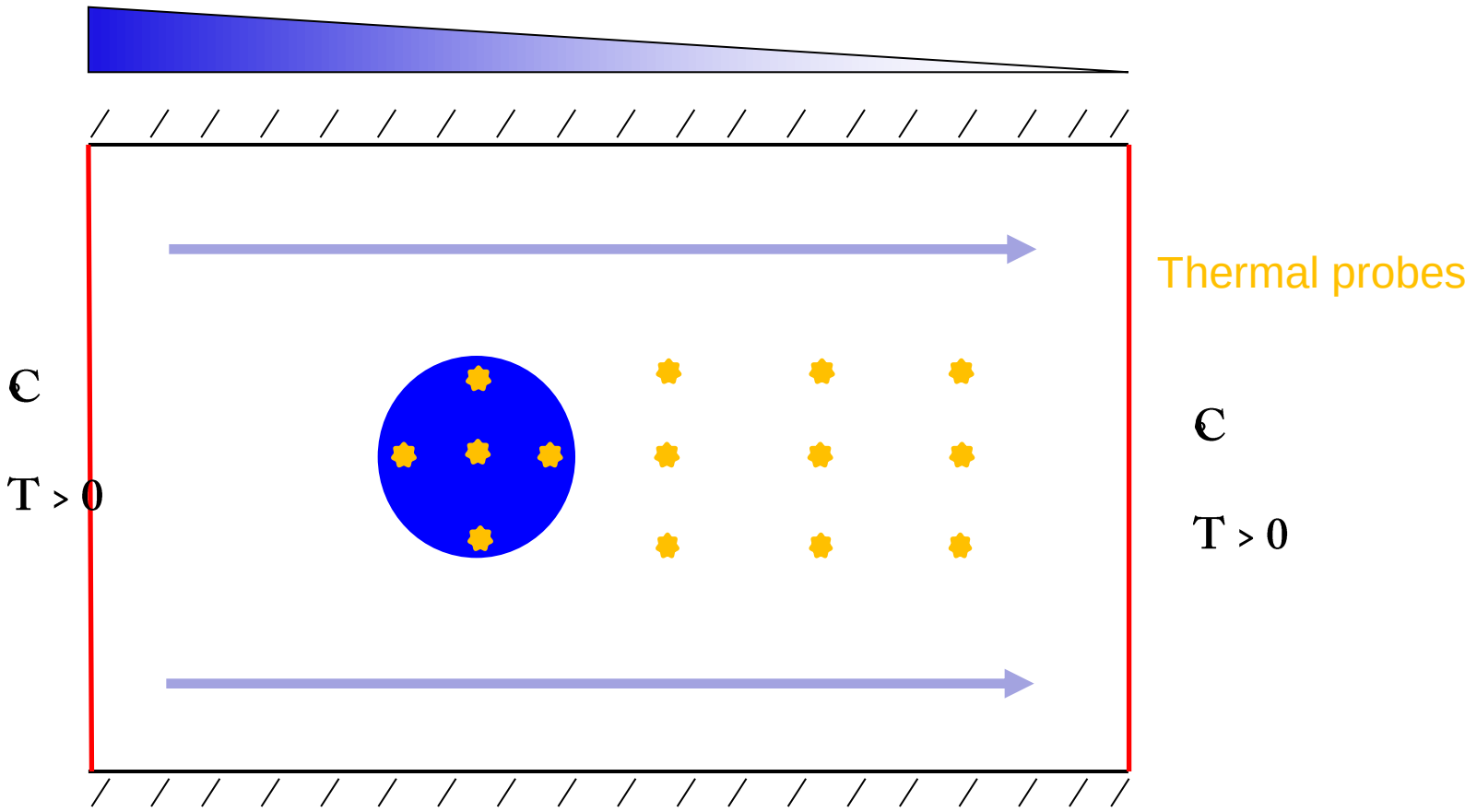




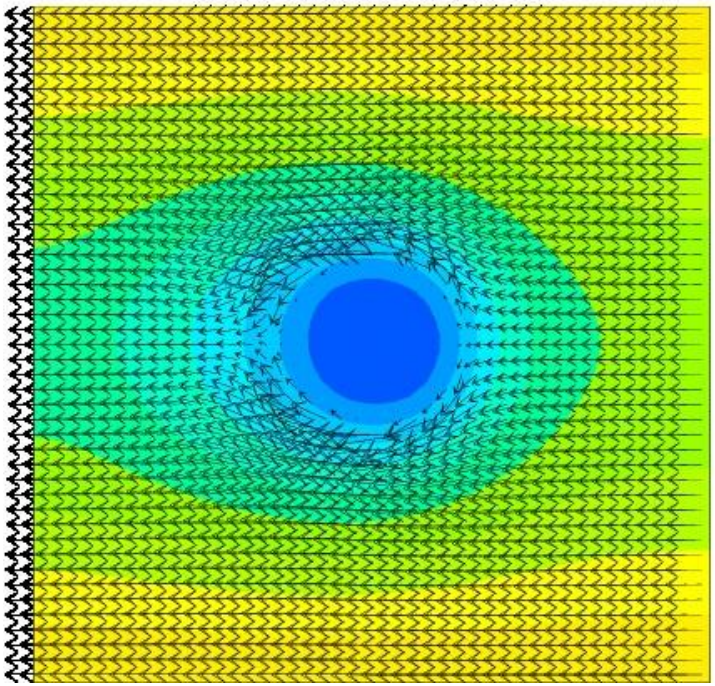


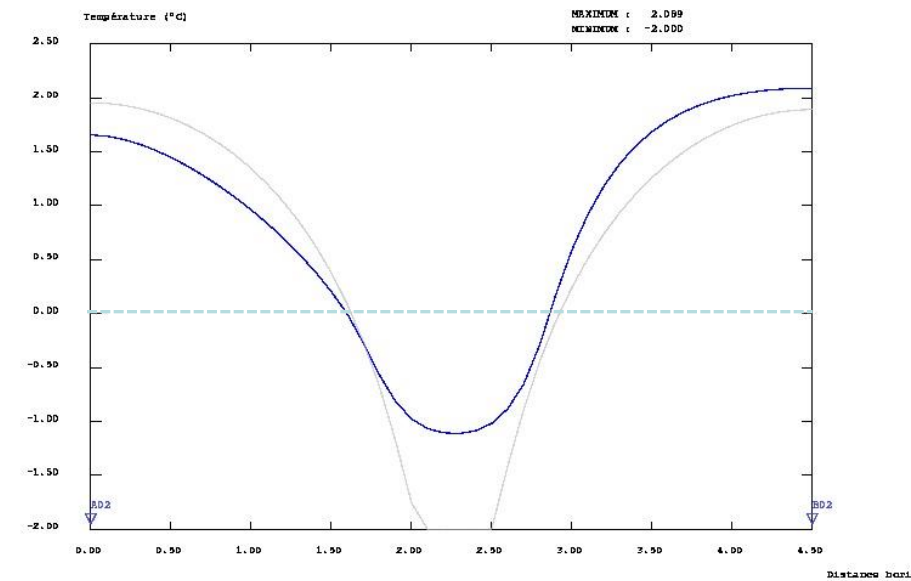
Lekmine et al 2011

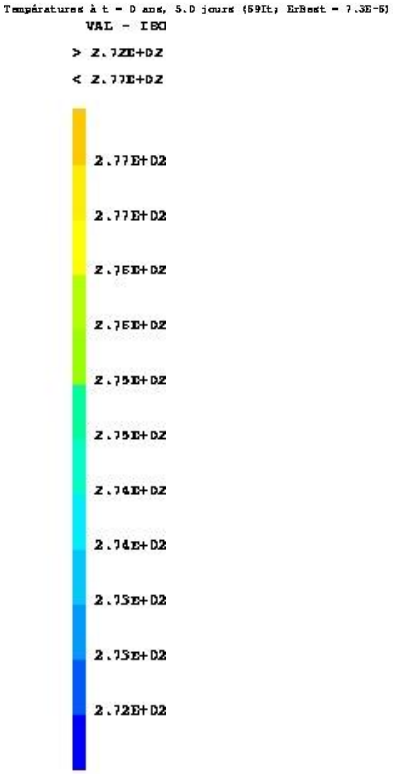
Task 3: « uniform » water flow

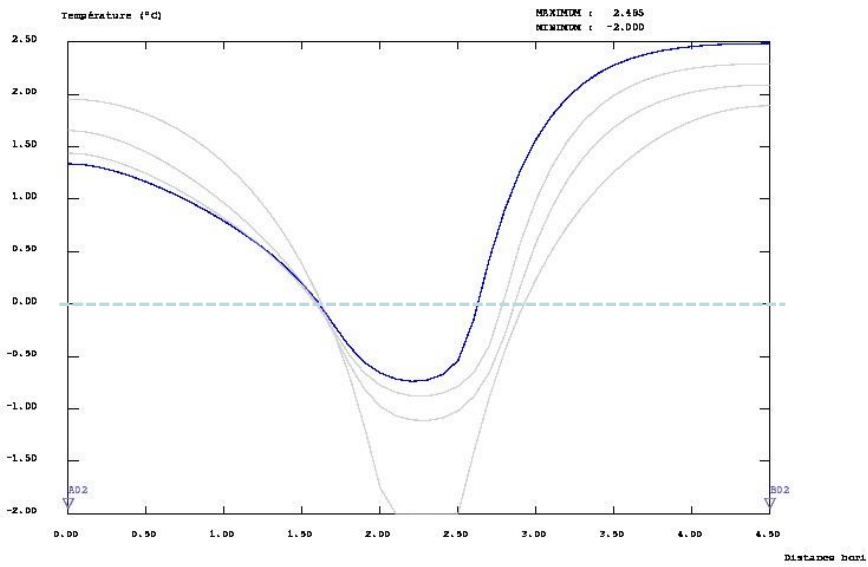


Ice bubble or frozen water inclusion

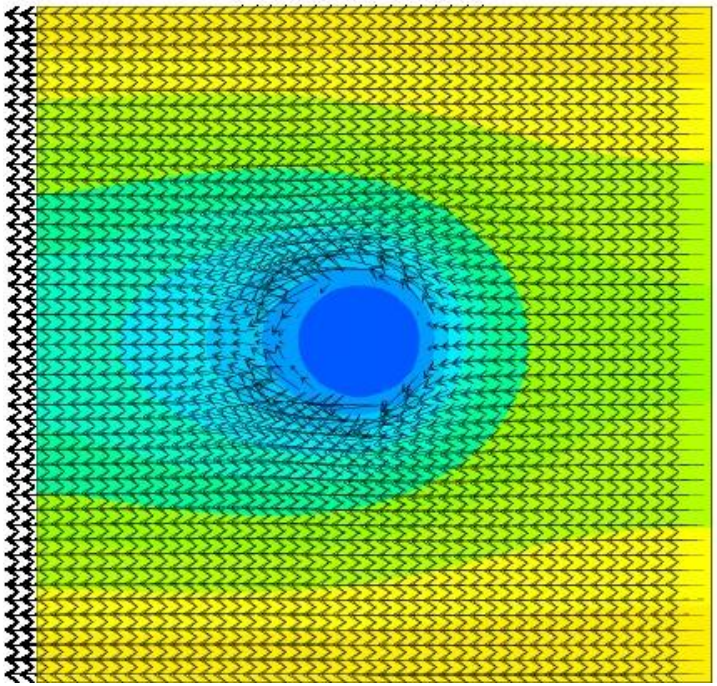


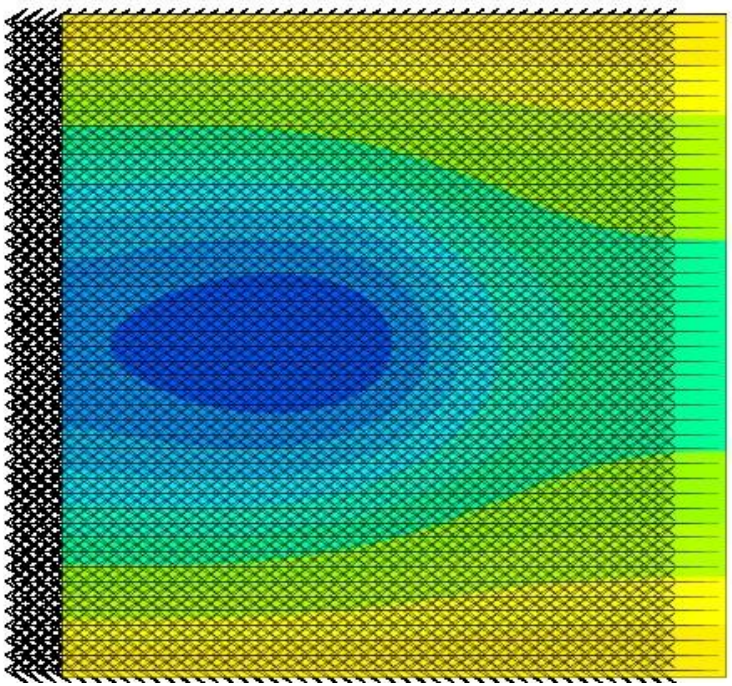

Température (°C)
MAXIMUM : 2.089
MINIMUM : -2.000
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
BD2
BD2
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
Distance hori

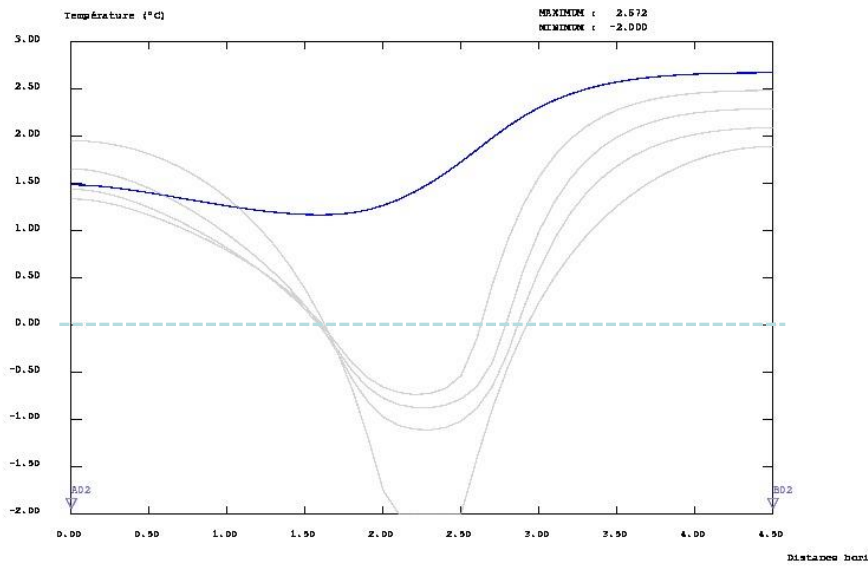

Températures à t = 0 ans, 5.0 jours (59It; ErBest = 7.3E-5)
VAL - IBC
> 2.72E+02
< 2.77E+02
2.77E+02
2.77E+02
2.76E+02
2.76E+02
2.75E+02
2.75E+02
2.74E+02
2.74E+02
2.73E+02
2.73E+02
2.72E+02



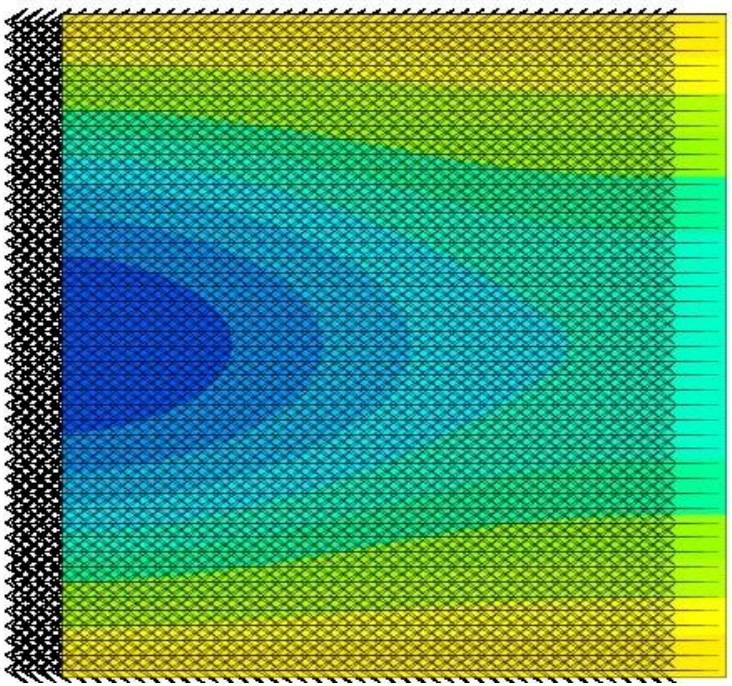
Températures à t = 0 ans, 15.0 jours (2000It; ErBest = 1.2E-3)

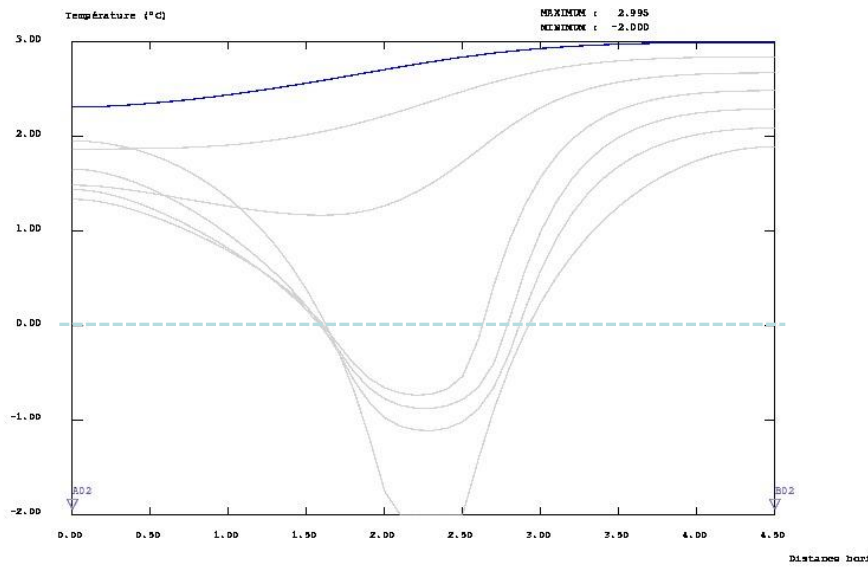






Températures à t = 0 ans, 20.0 jours (2000It; ErRest = 7.1E-4)





Températures à t = 0 ans, 30.0 jours (3DIt; ErBest = 8.8E-5)