Thermoelectric energy storage based on CO_2 transcritical cycles: ground heat storage modelling

Edoardo Gino Macchi[1], *Catherine Colin*[1], *Thomas Tartière*[2], *Denis Nguyen*[3], *Nicolas Tauveron*[4]

[1] IMFT, Université de Toulouse, 2 Allée du Professeur Camille Soula, 31400 Toulouse, France
[2] Enertime, 1 rue du Moulin des Bruyères, 92400 Courbevoie, France
[3] BRGM Languedoc-Roussillon, 1039 rue de Pinville, 34000 Montpellier, France
[4] CEA, LITEN – DTBH/SBRT/LS2T, 17 rue des Martyrs, 38054 Grenoble, France

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Outline

I. Introduction to energy storage & SeleCO2 project

II. Ground heat storage description and model

III. Mathematical and numerical model

    a. Quasi-steady flow model

    b. Unsteady model

IV. Simulations and results

V. Conclusions and future developments

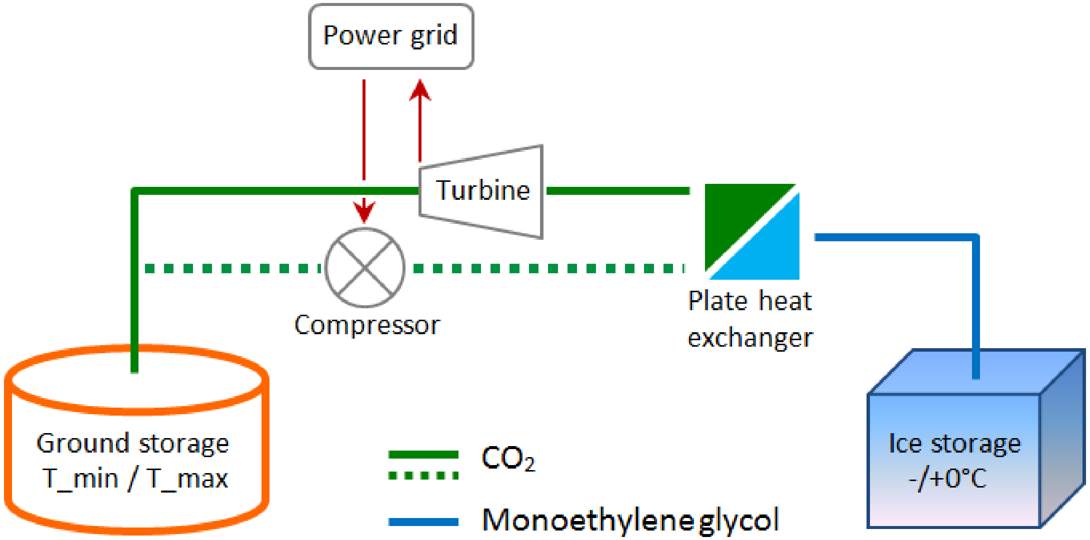
Energy storage technologies

- massive integration of renewable energy production (variable and uncertain output) generates new challenges for the regulation of electric grids;
- energy storage is essential for balancing supply and demand;
- current storage capacity is still limited (and almost exclusively from PHS);
- today's challenges are to increase the storage capacities and efficiencies.

SeleCO2 project

Large scale thermoelectric energy storage based on underground heat storage & ice storage system using CO_2 as the working fluid

Project website: http://seleco2.free.fr



SeleCO2 project

Large scale thermoelectric energy storage based on underground heat storage & ice storage system using CO_2 as heat transfer fluid

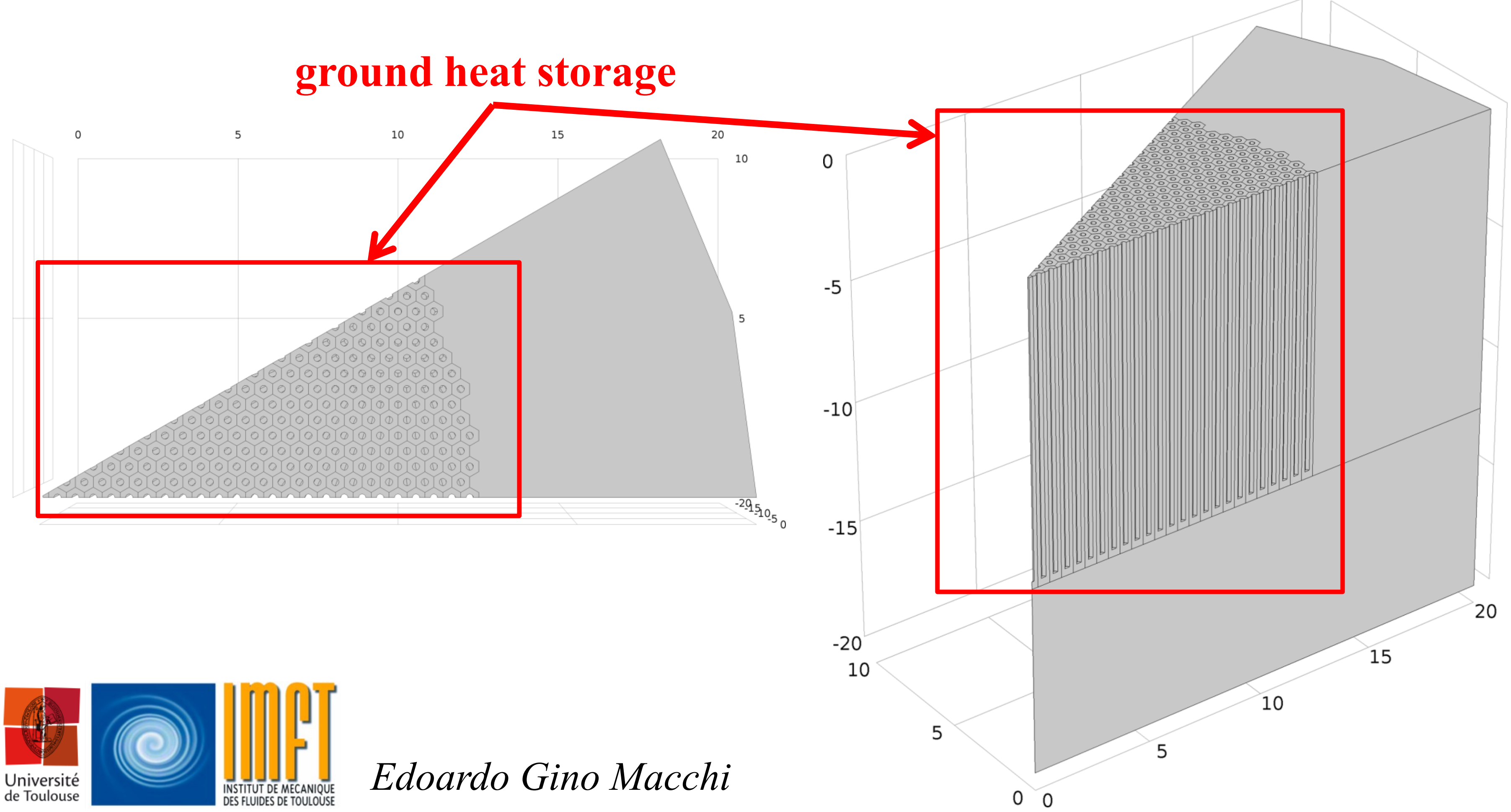
Project website: **http://seleco2.free.fr**

Main expected results:

- preliminary design of the ground storage as well as storage model development;
- experimental study on a single heat exchanger (1:10 prototype);
- development of a tool for modelling the whole process and optimizing the system;
- feasibility study and economic analysis.

Ground heat storage description

- made of 2160 vertical boreholes (interaxis 0.5 m) drilled in a shallow rock massif;
- serial-parallel layout: 48 parallel series of 45 exchangers;



Ground heat storage description

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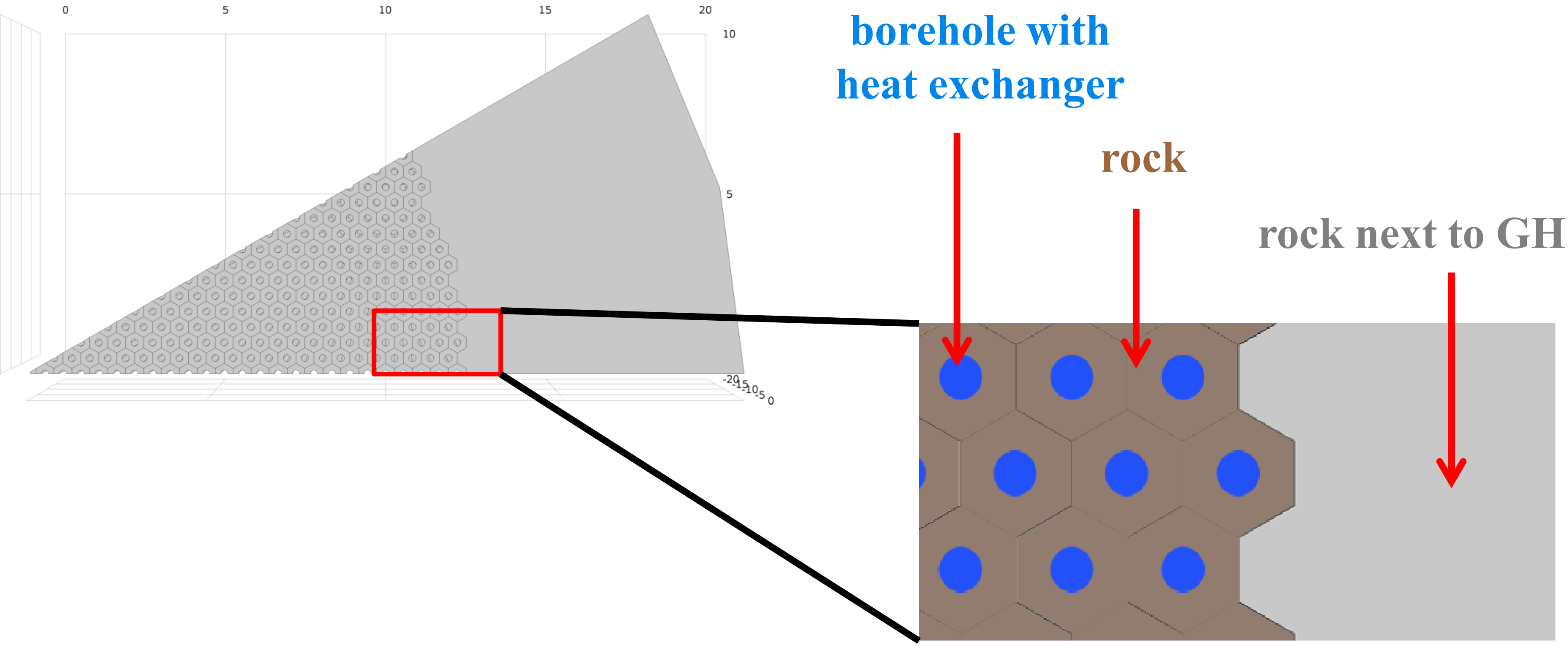
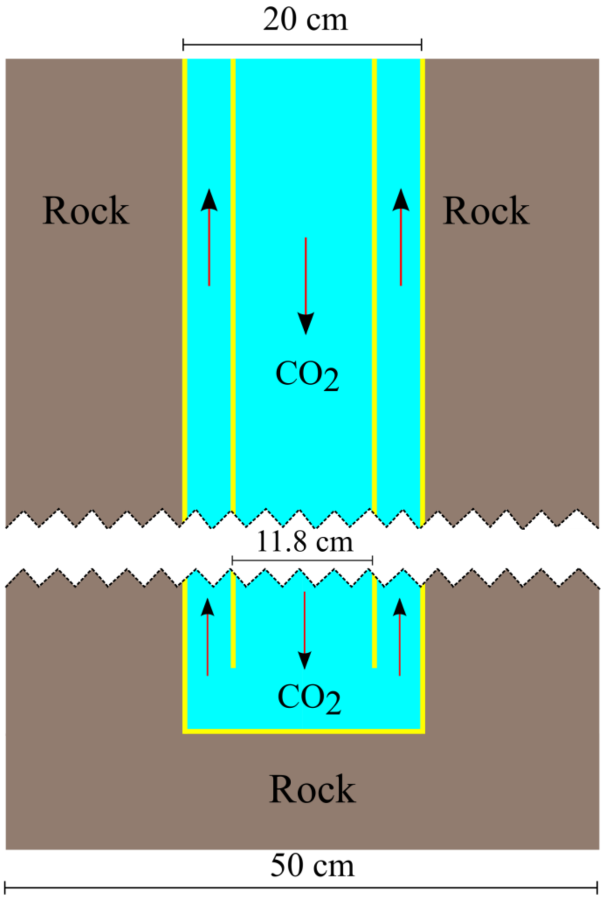


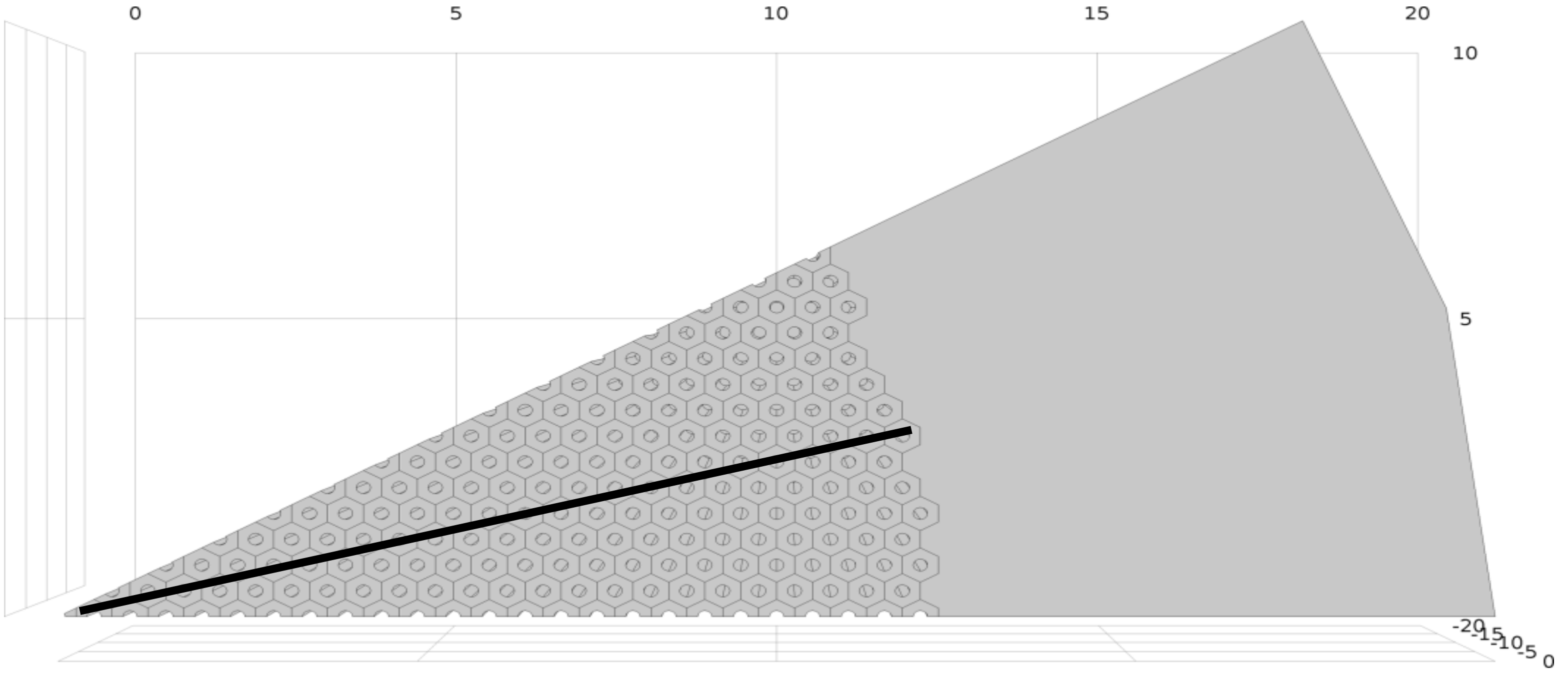
Ground heat storage description

- each borehole hosts a rubber casing that converts it in a geothermal exchanger;
- rubber casing includes a central circular injection pipe and an annular return;



Ground heat storage description

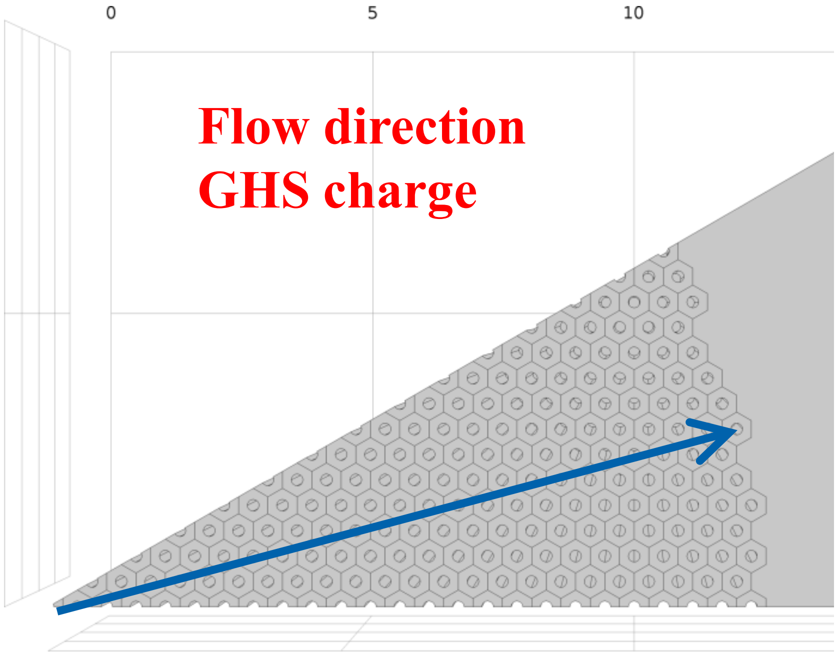
- exchangers in a series are approximately positioned along a radius;

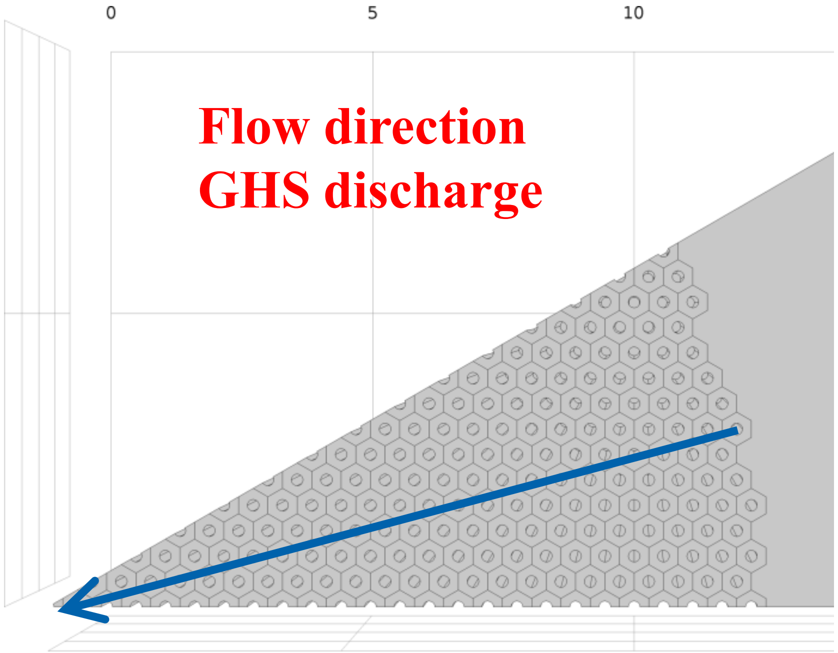


Ground heat storage description

- exchangers in a series are approximately positioned along a radius;
- flow direction: from 1st (central) to 45th (peripheral) exchanger during storage charge and the opposite during discharge; →

peripheral exchangers are the coldest so heat losses are minimized





Ground heat storage model

GHS modelling difficulties

- high Reynolds number flow in the exchangers (Re ~ 10^5 -10^6);
- fluid-rock time scale disparity;
- GHS behaviour during several charge/discharge cycles must be investigated;
- large size of the system to be modelled (even considering only one series of 45 exchangers);
- possibly high degree of unsteadiness of the system.

- conjugate heat transfer CFD simulation (RANS) feasible only for a single exchanger;
- modelling tool for performing the optimization of the whole GHS is required;
- simplified and fast model must be developed.

Ground heat storage model

○ approximations about the physics should be minimal since model validation will be difficult;

○ geometrical approximations are introduced:

- only single series of 45 exchangers is modelled;
- 2D/1D axisymmetric model for the heat transfer inside the rock;
- 1D model for the thermo-fluid dynamic behaviour of CO_2 inside the exchangers.

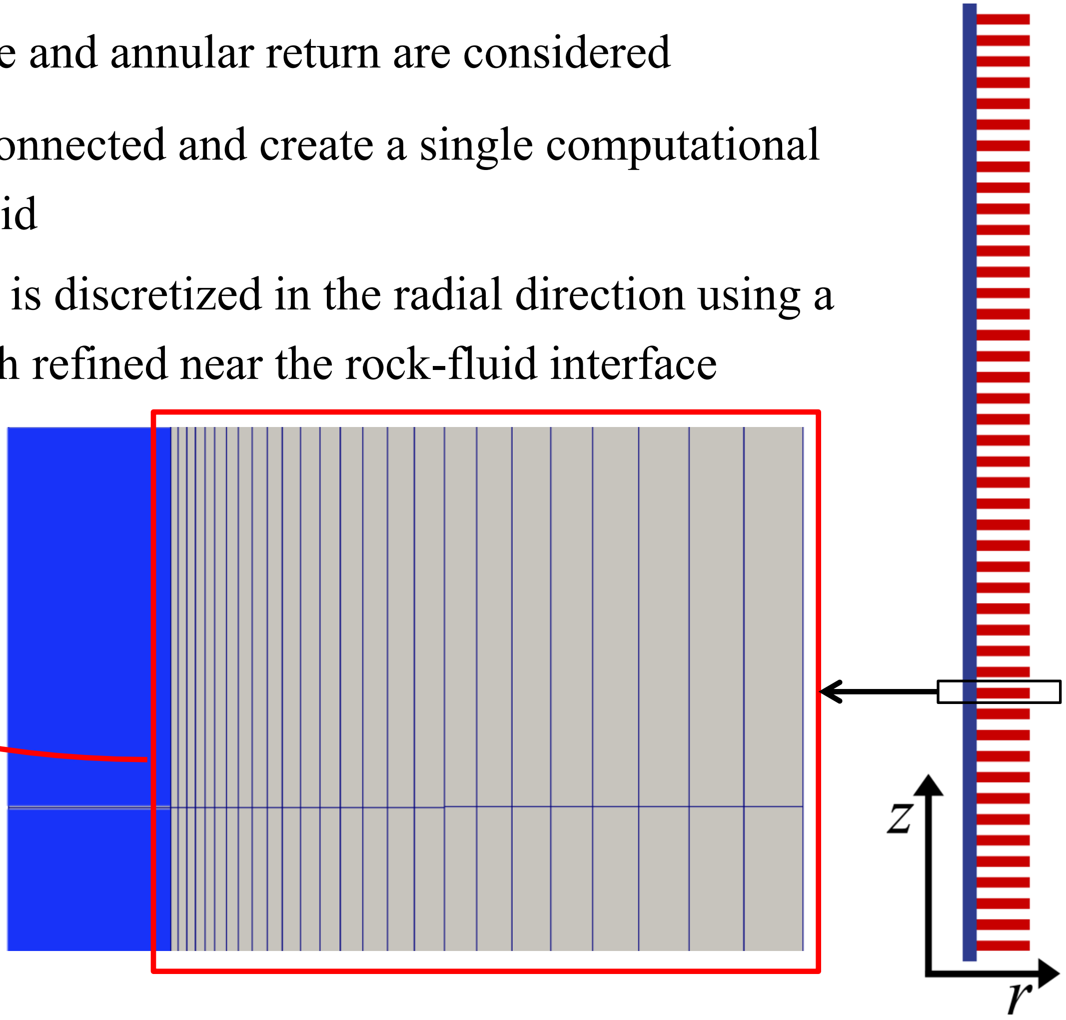
○ interactions between the exchangers (i.e., heat conduction between the rock surrounding each exchanger) and the heat losses toward the rock surrounding the whole heat storage are assumed to be negligible

Reasonable since:

- temperature differences between adjacent exchangers are small;
- heat losses are significant only during the start-up phase.

Ground heat storage model

- both injection pipe and annular return are considered
- all the pipes are connected and create a single computational domain for the fluid
- each rock domain is discretized in the radial direction using a non-uniform mesh refined near the rock-fluid interface



red: rock

blue: fluid

(deformed along radial direction)

- 25 cells
- ratio first to last cell size: 1/8

Quasi-steady flow model

- quasi-steady model for the **fluid**

$$\begin{cases} \dfrac{\partial(\rho U A)}{\partial z} = 0 \quad \Rightarrow \quad U = \dfrac{G}{\rho A} \\[2ex] \dfrac{1}{A}\dfrac{\partial(\rho U U A)}{\partial z} = -\dfrac{\partial p}{\partial z} - \dfrac{f \rho U |U|}{2D_h} \\[2ex] \dfrac{1}{A}\dfrac{\partial(\rho U h A)}{\partial z} = q \longrightarrow \boxed{q_i = \dfrac{Q_i}{V_i} = \dfrac{\Gamma_i S_i \left(T_{w_i} - T_i\right)}{V_i}} \\[2ex] \rho = \rho(h, p) \\ T = T(h, p) \end{cases}$$

$$f = \mathrm{f}\left(Re, \frac{\varepsilon}{D}, T, P, T_w\right)$$

(Fang et al., 2012)

$$\Gamma = \mathrm{f}\left(Re, Pr, Gr, T_w\right)$$

(Kirillov, 1990)
(Pioro et al., 2004)

Quasi-steady flow model

- quasi-steady model for the **fluid**
- unsteady model for the heat conduction in the **rock**

$$
\begin{cases}
\dfrac{\partial(\rho U A)}{\partial z} = 0 \quad \Rightarrow \quad U = \dfrac{G}{\rho A} \\[2ex]
\dfrac{1}{A}\dfrac{\partial(\rho U U A)}{\partial z} = -\dfrac{\partial p}{\partial z} - \dfrac{f \rho U |U|}{2 D_h} \\[2ex]
\dfrac{1}{A}\dfrac{\partial(\rho U h A)}{\partial z} = \textcircled{q} \longrightarrow \boxed{q_i = \dfrac{Q_i}{V_i} = \dfrac{\Gamma_i S_i \left(T_{w_i} - T_i\right)}{V_i}} \\[2ex]
\rho = \rho(h, p) \\[1ex]
T = T(h, p)
\end{cases}
$$

$$
\boxed{\rho_R C_{pR} \frac{\partial T_R}{\partial t} = \lambda_R \left[\frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T_R}{\partial r} \right) + \frac{\partial^2 T_R}{\partial z^2} \right]}
$$

on the rock-fluid boundary:

$$
-\lambda_R \frac{\partial T_R}{\partial r} = \Gamma\left(T - T_R\right) = -\frac{Q_i}{S_i}
$$

fluid-rock coupling

might be too restrictive since:

$$
t_c = \frac{L}{U} \cong \frac{2000}{1} = 2000 \ s
$$

Unsteady model

- unsteady model for both **fluid** and **rock**

$$\begin{cases} \dfrac{\partial \rho}{\partial t}+\dfrac{1}{A}\dfrac{\partial(\rho U A)}{\partial z}=0 \\[2ex] \dfrac{\partial(\rho U)}{\partial t}+\dfrac{1}{A}\dfrac{\partial(\rho U U A)}{\partial z}=-\dfrac{\partial p}{\partial z}-\dfrac{f\rho U|U|}{2D_h} \\[2ex] \dfrac{\partial(\rho h)}{\partial t}+\dfrac{1}{A}\dfrac{\partial(\rho U h A)}{\partial z}=q \\[2ex] \rho=\rho(h,p) \\ T=T(h,p) \end{cases}$$

$$\rho_R C_{pR}\frac{\partial T_R}{\partial t}=\lambda_R\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_R}{\partial r}\right)+\frac{\partial^2 T_R}{\partial z^2}\right]$$

on the rock-fluid boundary:

$$-\lambda_R\frac{\partial T_R}{\partial r}=\Gamma(T-T_R)=-\frac{Q_i}{S_i}$$

$$q_i=\frac{Q_i}{V_i}=\frac{\Gamma_i S_i\left(T_{w_i}-T_i\right)}{V_i}$$

fluid-rock coupling

Model implementation

- both models have been implemented within the OpenFOAM® framework;
- equations have been discretised using a 2nd order accurate finite volume method;
- the opensource library CoolProp is used to compute the thermodynamic and transport properties of CO_2 while constant properties are used for the rock (assumed to be granite): ρ_R = 2650 kg/m^3, C_{pR} = 790 J/kgK, λ_R =3.4 W/mK;
- in both models the governing equations are solved separately and suitable iterative algorithms have been implemented to reach the desired convergence;
- in the unsteady model:
  - the PISO algorithm has been used to compute the fluid' dependent variables (U , p and h);
  - an adaptive time-stepping method based on the maximum allowable Courant number has been adopted;
- simulations have been run in parallel using 6 cores on a Xeon E5-2623 3.0 GHz workstation with 32 GB of RAM.

Initial and boundary conditions

- fluid enthalpy and density are initialized assuming uniform fluid temperature and pressure (303.15 K and 12 MPa);
- the fluid is assumed to be still at the beginning of the simulation, as well as, at the beginning of each charge or discharge;
- for all the exchangers the initial temperature of the rock is 303.15 K;
- concerning the boundary conditions:
    - for the rock temperature homogeneous Neumann b.c. are applied on all boundaries but the rock-fluid interface where a convective b.c. is used;
    - concerning the fluid, standard inflow/outflow boundary conditions are used for velocity and pressure (assigning mass flow rate/velocity at the inlet and pressure at the outlet), the fluid enthalpy is assigned at the inlet and a homogeneous Neumann boundary condition on enthalpy is applied at the outlet of the series of exchangers.

Simulations parameters

Some parameters are kept constant in all the simulations, in particular:

- number of exchangers: 45;
- exchanger inner/outer diameter: ~ 12/20 cm;
- outlet pressure: 12 MPa;
- inlet temperature during charge: 411.15 K;
- inlet temperature during discharge: 303.15 K;
- pipe roughness: 2 µm.

Initial simulation - parameters

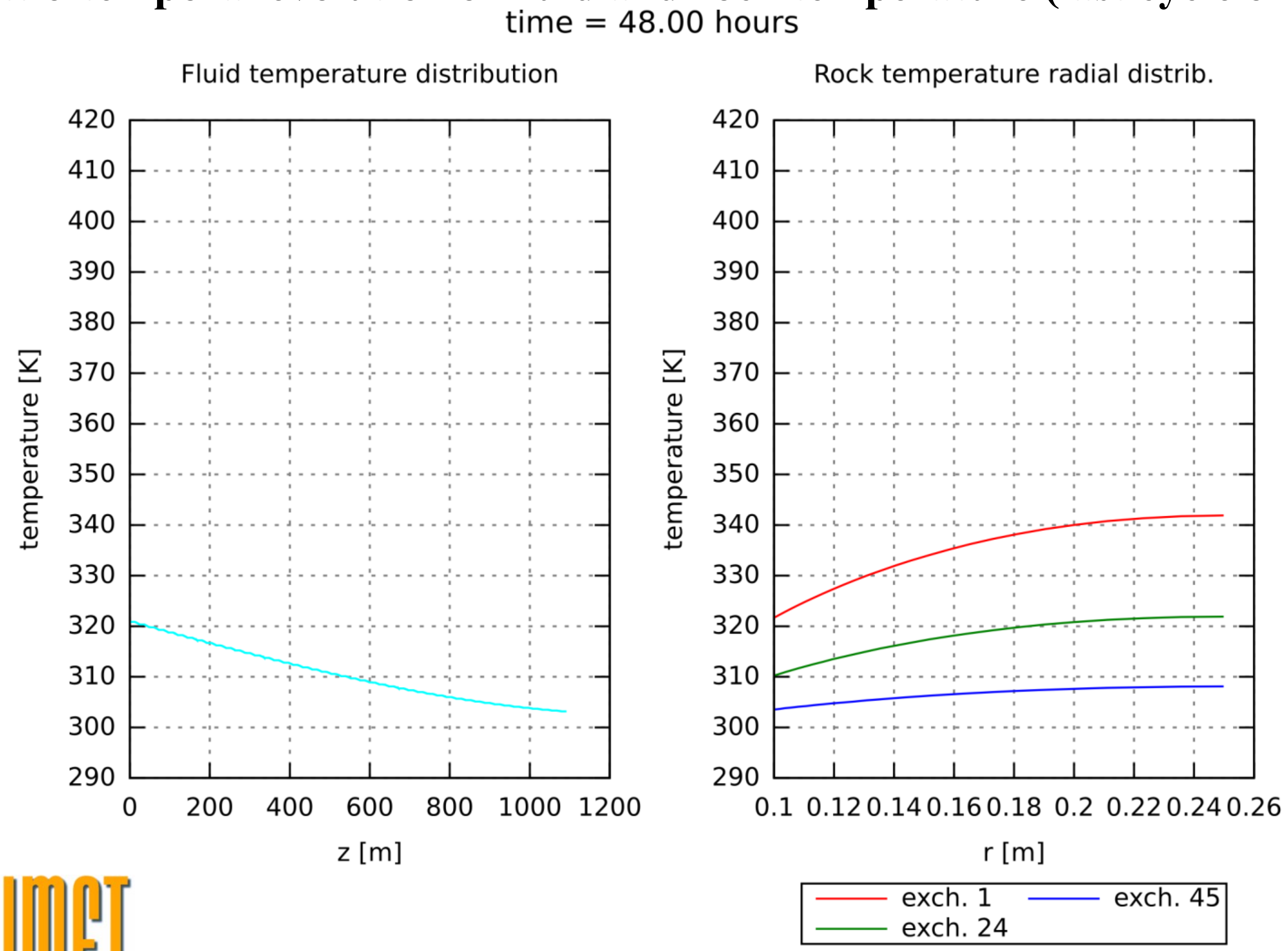
Modelling 5 consecutive charge/discharge cycles with:

• exchanger length:	$L_{exch} = 12$ m
• charge duration:	$t_{charge} = 6$ hours
• mass flow rate during charge:	$G_{charge} = 4$ kg/s
• discharge duration:	$t_{discharge} = 6$ hours
• mass flow rate during discharge:	$G_{discharge} = 4$ kg/s

Initial simulation - results

Spatio-temporal evolution of fluid and rock temperature (last cycle only)

Video



Numerical tests

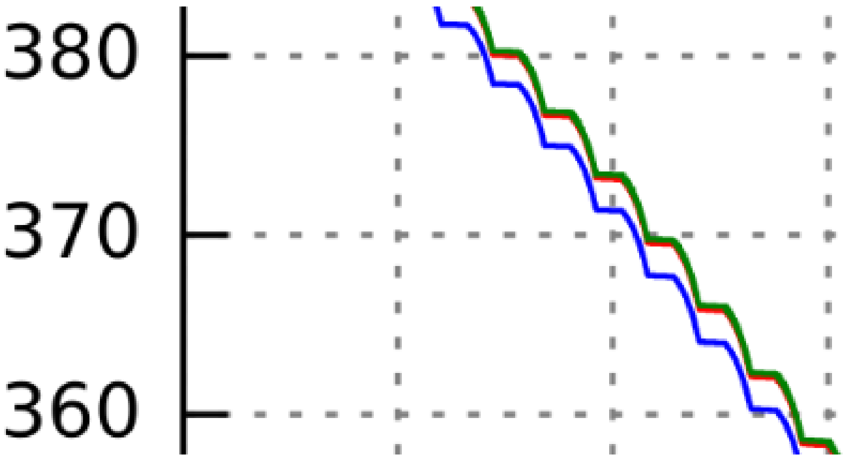
- sensitivity analysis on mesh and time-step size;
- comparison quasi-steady flow and fully unsteady model;
- comparison 1D/2D (fluid/rock) and 1D/1D models;

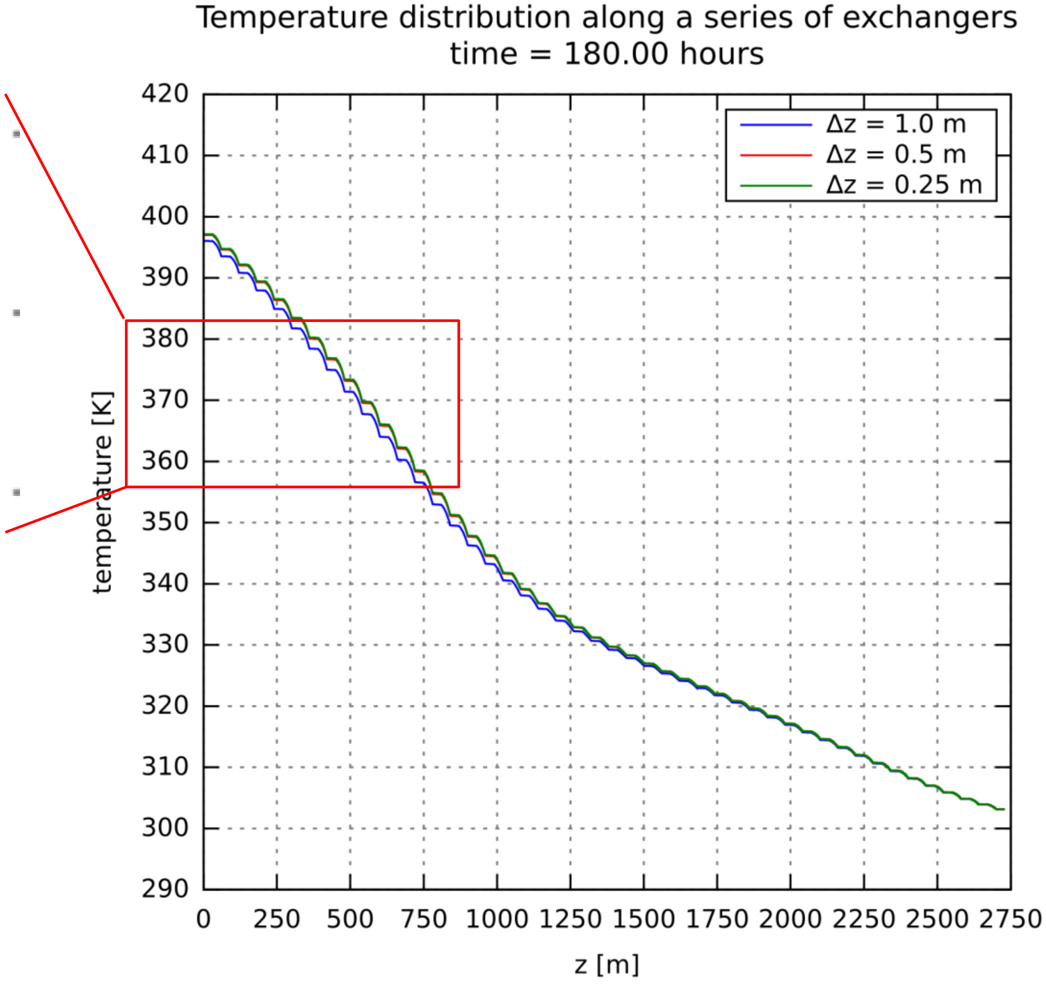
Tests performed on two different configurations:

	N° cycles	**L_{exch}** (m)	**t_{charge}** (hours)	**G_{charge}** (kg/s)	**$t_{discharge}$** (hours)	**$G_{discharge}$** (kg/s)
Case A	5	12	6	4	6	4
Case B	18	30	6	1.75	4	2.5

Sensitivity analysis on mesh size

Simulation Case B (unsteady model and 1D/1D approach)





selected z-dir
cell size: **0.5 m**

Sensitivity analysis on mesh size

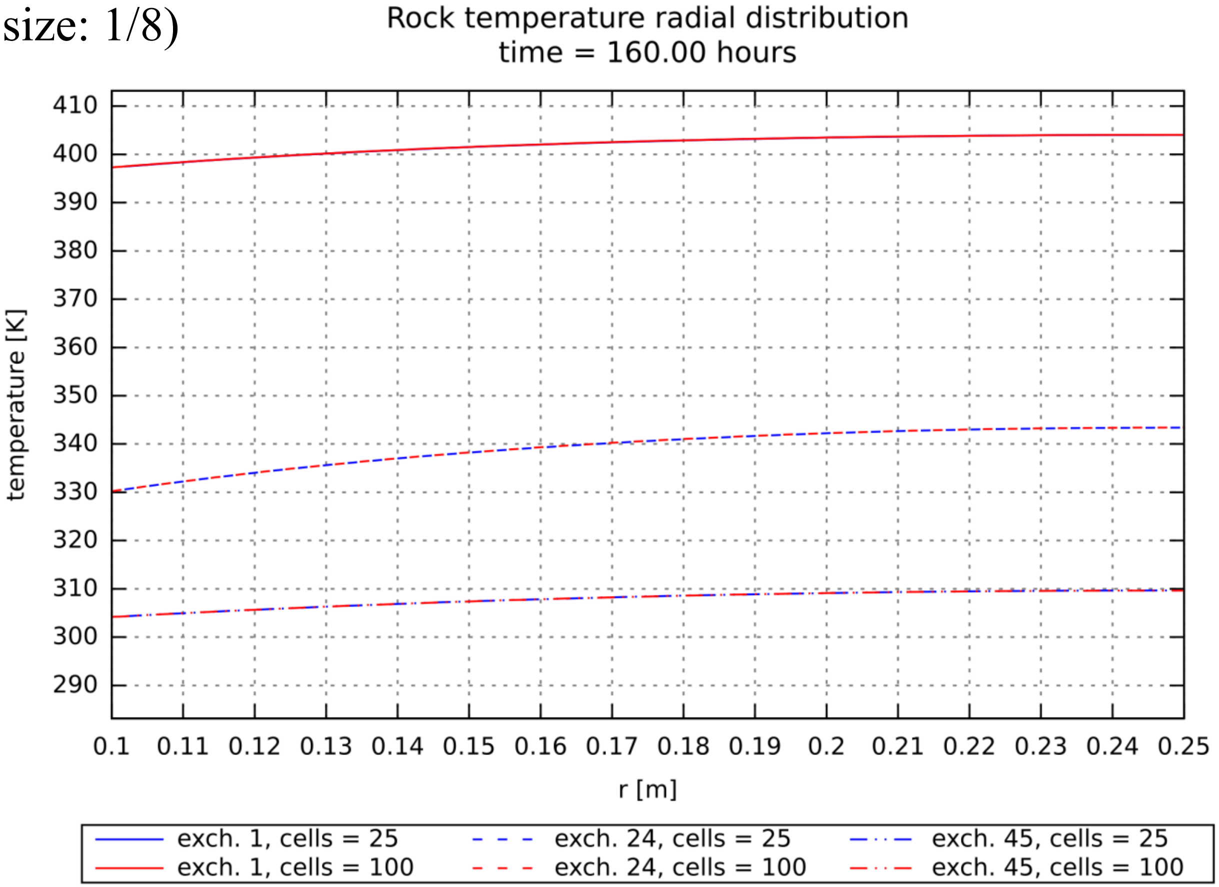
Simulation Case B (unsteady model and 1D/1D approach)

Sensitivity analysis performed also on rock mesh size

n. cells radial direction: 12, 25, 50, 100

(keeping the ratio first to last cell size: 1/8)

- very small changes
- discretization chosen : **25 cells**

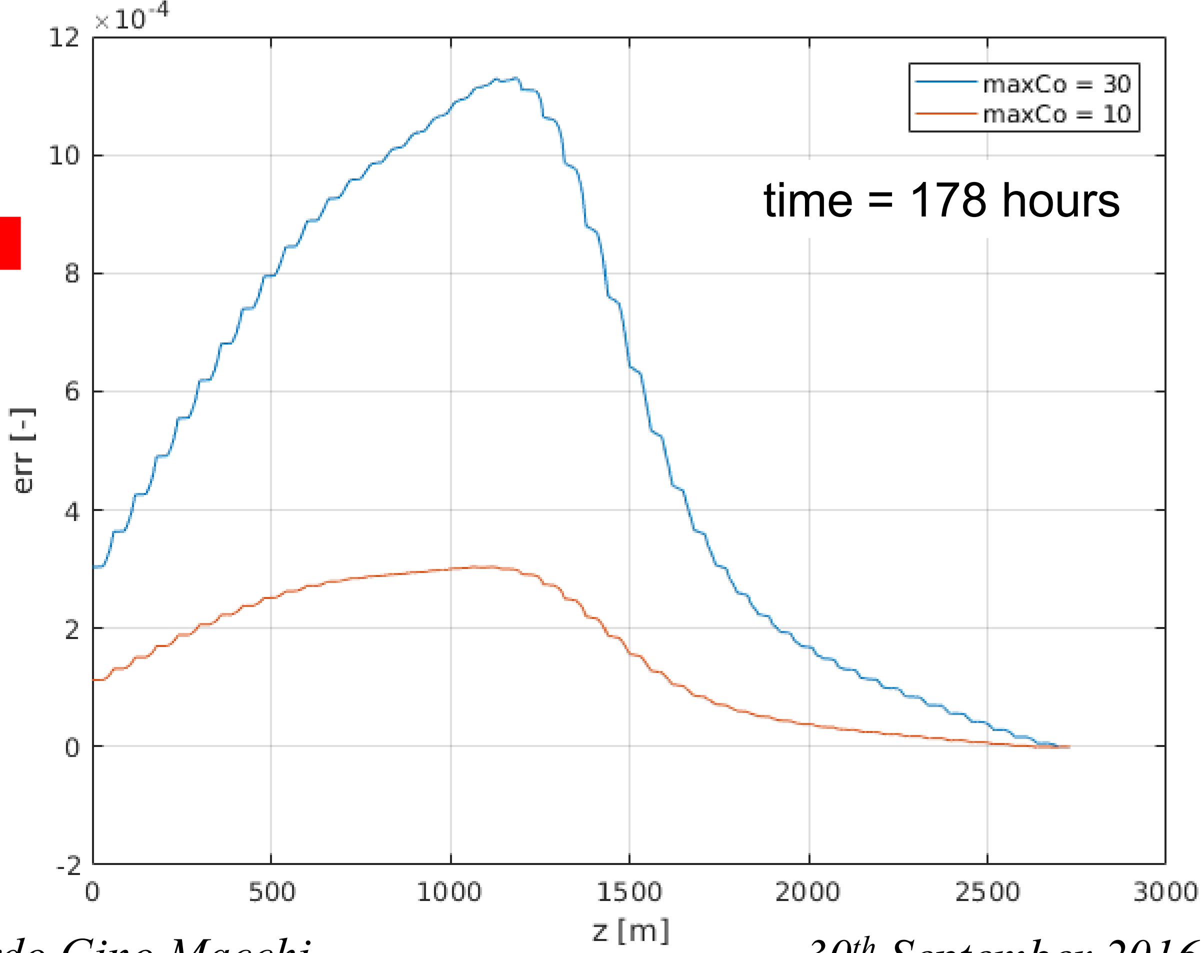


Sensitivity analysis on time-step size

Simulation Case B (unsteady model and 1D/1D approach)

Relative error on fluid temperature distribution (simulation w/ maxCo=1 used as reference)

simulation stable and accurate even w/ high maxCo

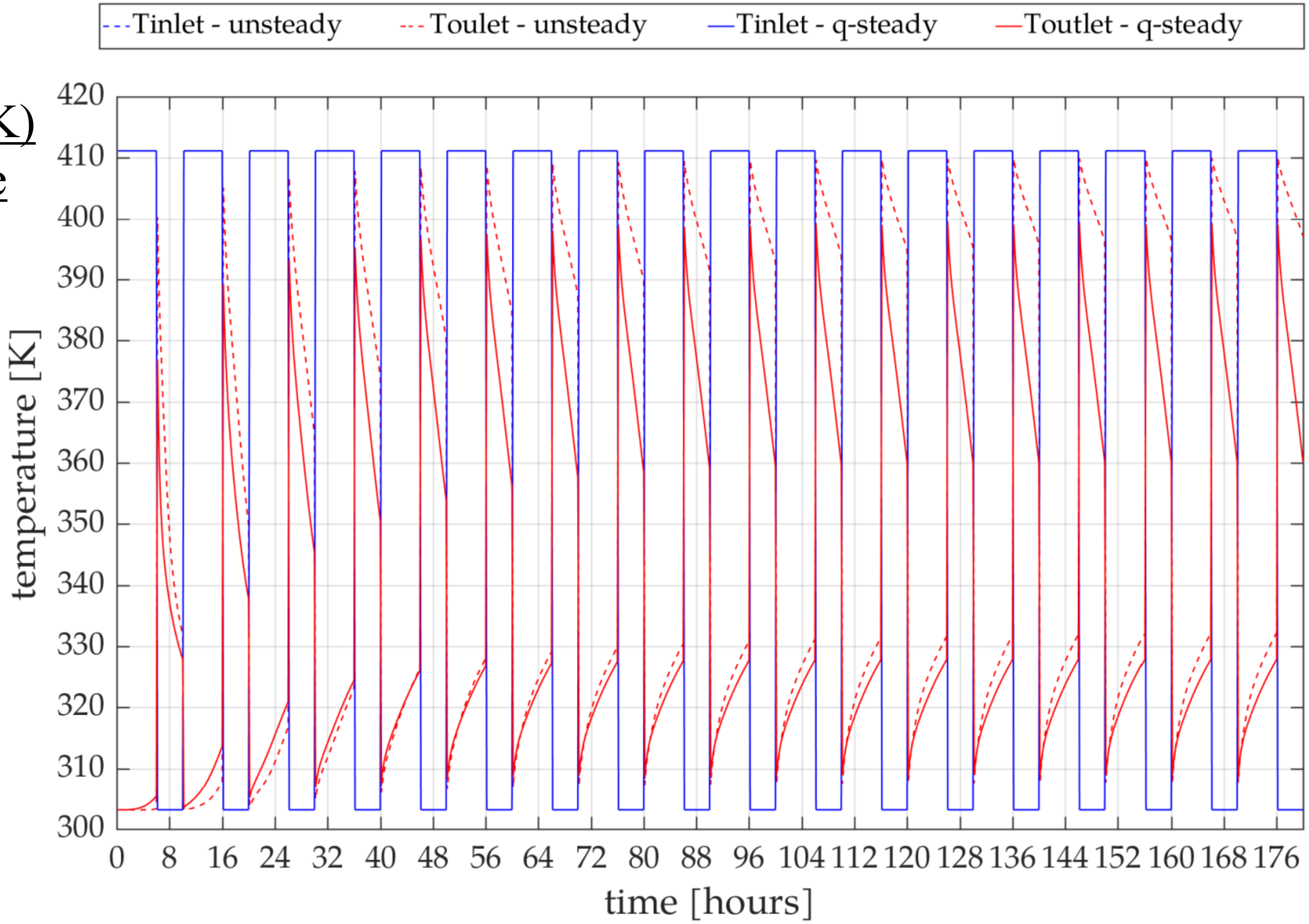


Comparison quasi-steady flow & unsteady model

Simulation Case B (1D/1D approach)

Evolution of inlet & outlet fluid temperature

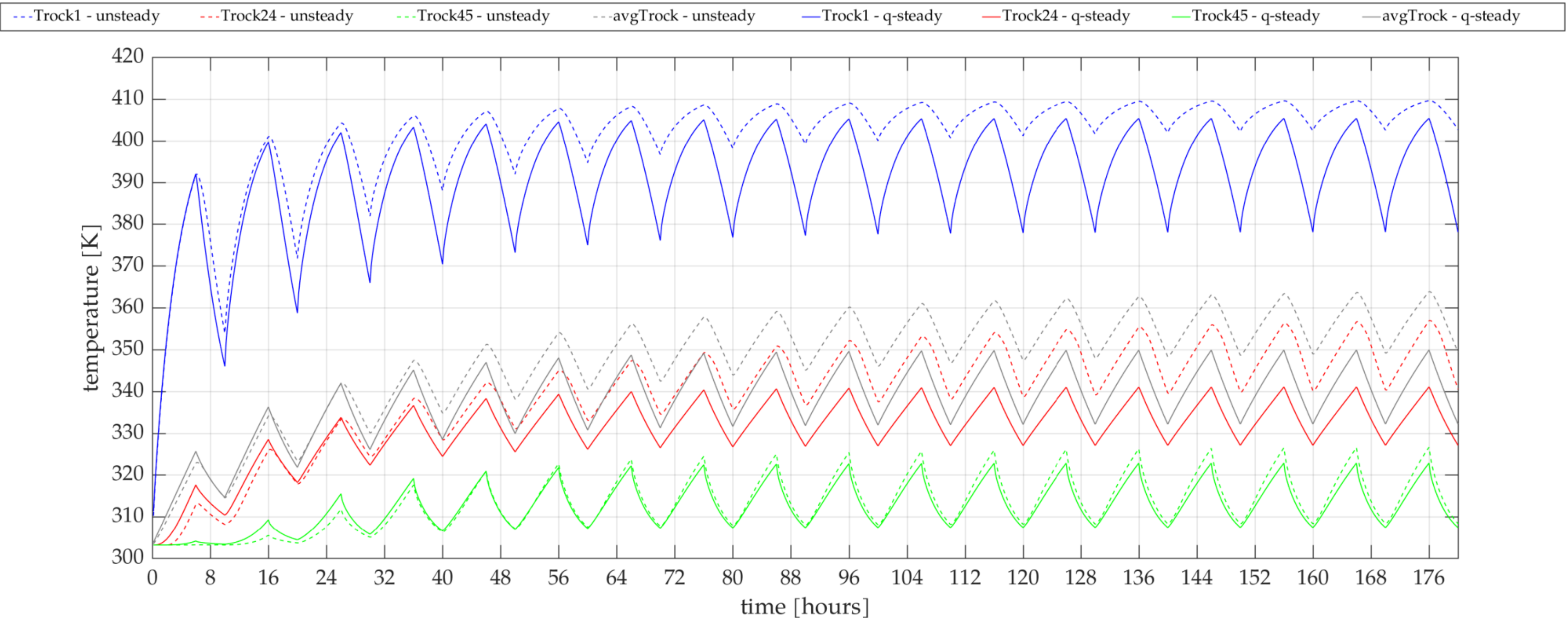
very large differences (> 30 K) in particular during discharge



Comparison quasi-steady flow & unsteady model

Simulation Case B (1D/1D approach)

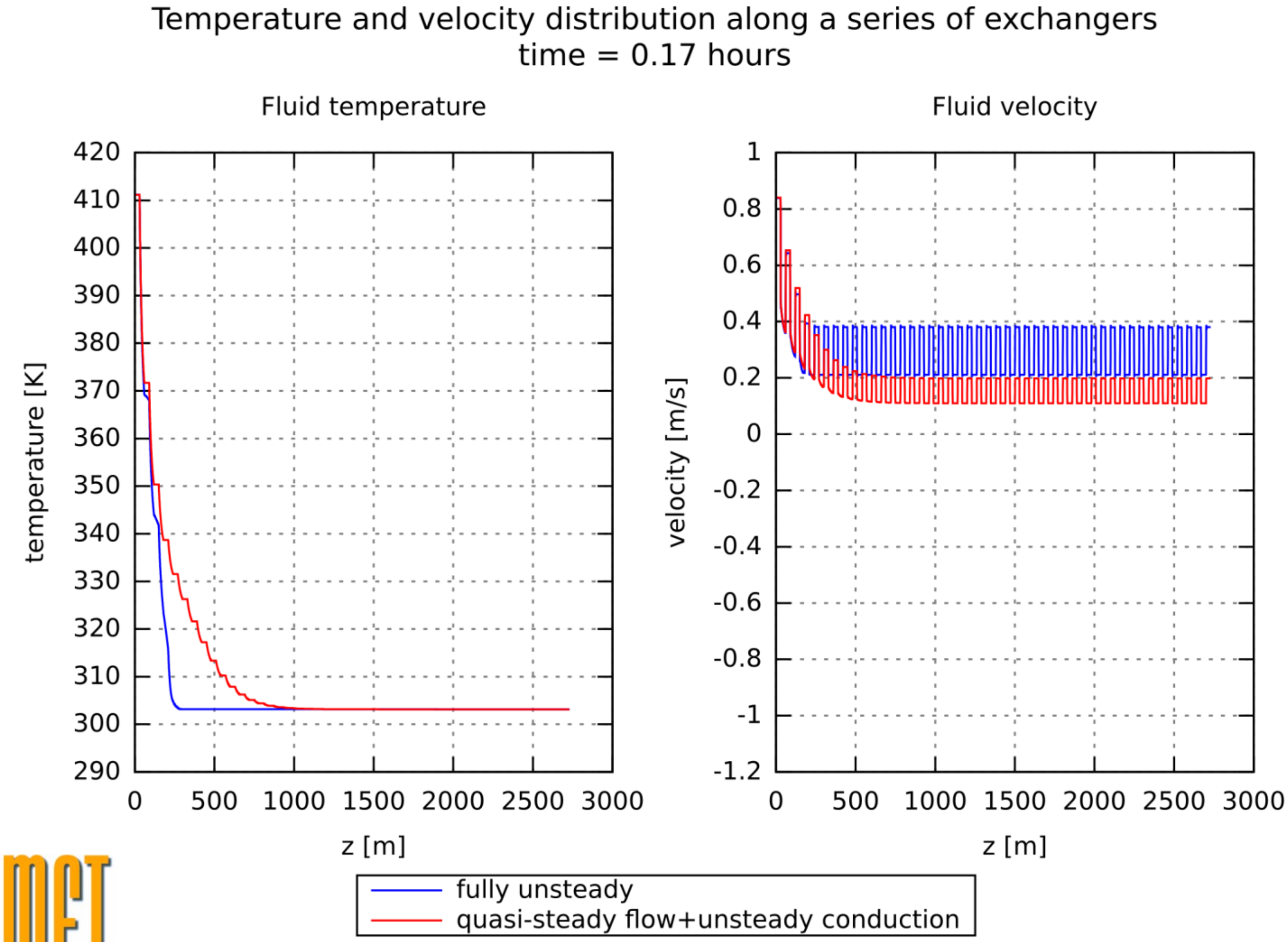
Evolution of volume-averaged rock temperatures



Comparison quasi-steady flow & unsteady model

Simulation Case B (1D/1D approach)

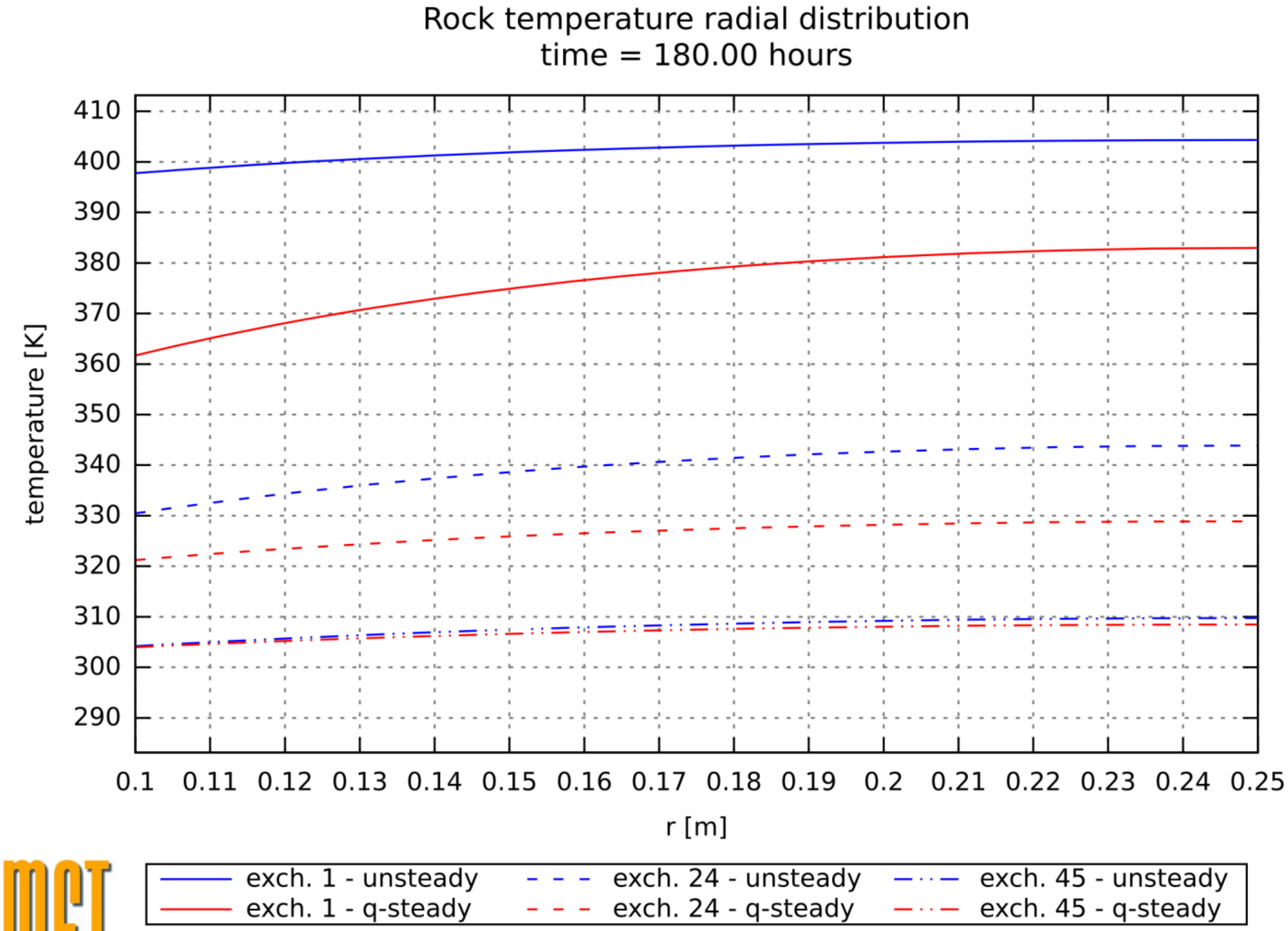
Video



Comparison quasi-steady flow & unsteady model

Simulation Case B (1D/1D approach)

Video



Comparison 1D/2D & 1D/1D model

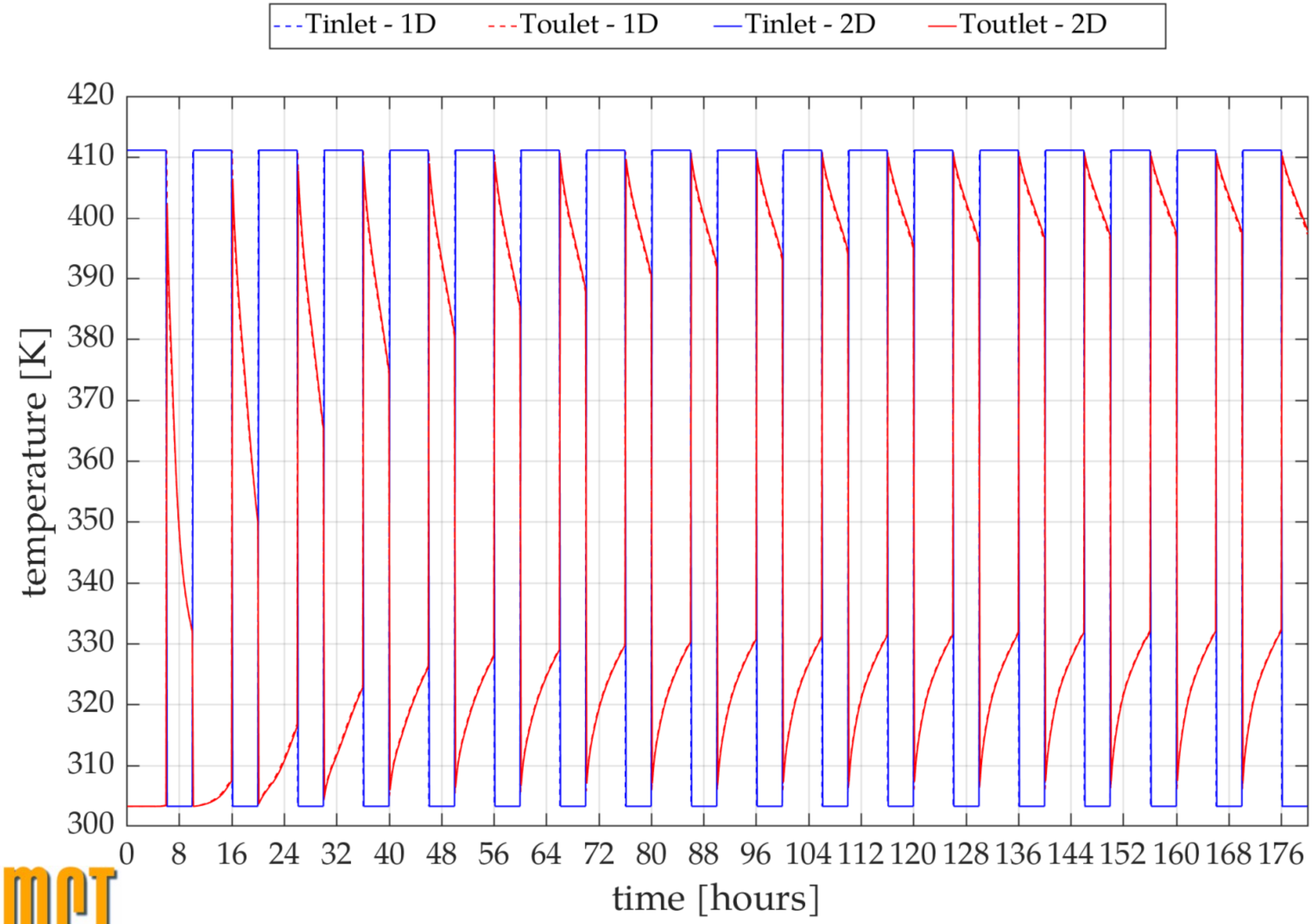
Simulation Case B

- analysis 1D/2D simulation: temperature profiles at different heights (top, center, bottom) for 1st, 24th and 45th exchanger;
- evolution radial temperature profile: comparison 2D (central) vs. 1D;
- comparison temporal evolution of "global" variables (fluid temperature at outlet and average rock temperatures).

Comparison 1D/2D & 1D/1D model

Simulation Case B

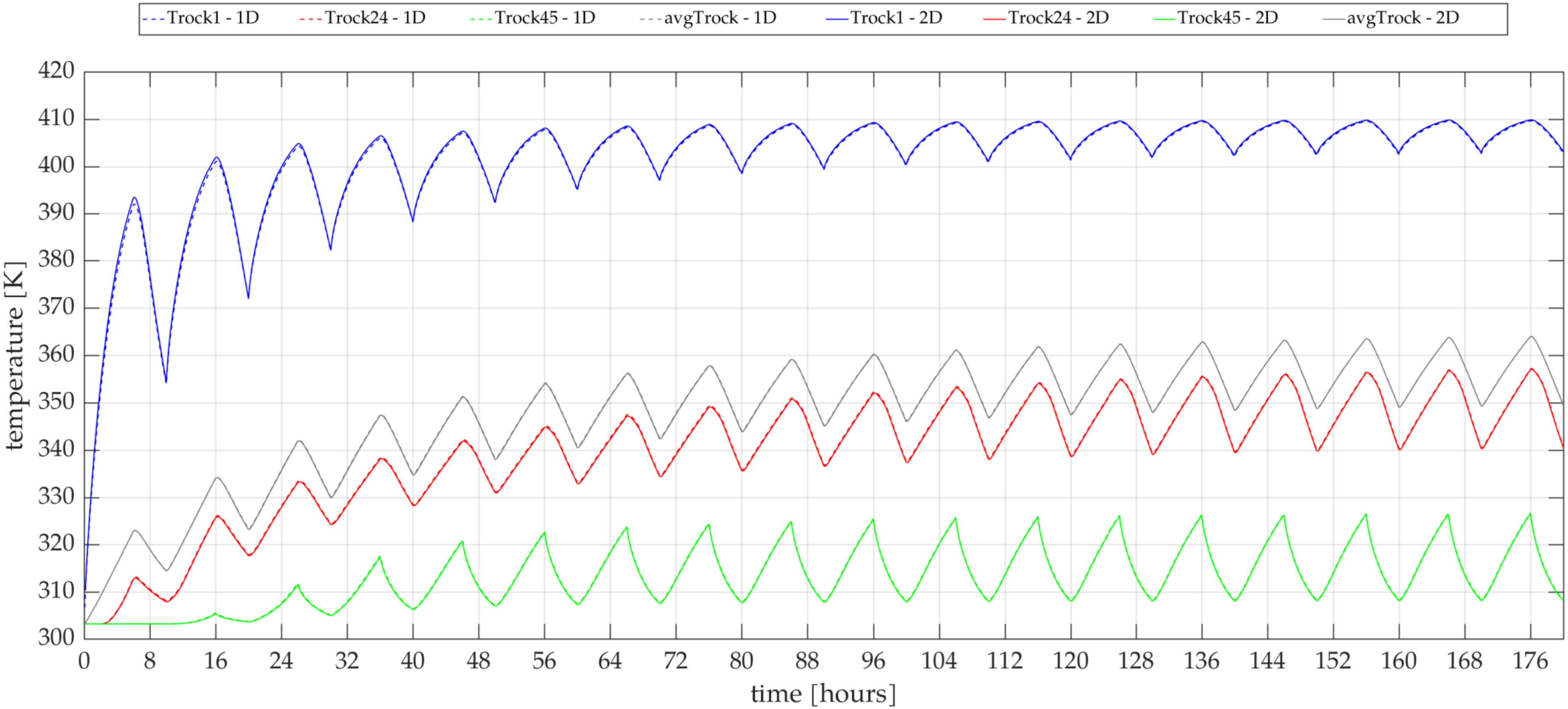
Evolution of inlet and outlet temperature



Comparison 1D/2D & 1D/1D model

Simulation Case B

Evolution of volume-averaged rock temperatures



Comparison 1D/2D & 1D/1D model

Simulation Case B

- analysis 1D/2D simulation: temperature profiles at different heights (top, center, bottom) for 1st, 24th and 45th exchanger (video);
- evolution radial temperature profile: comparison 2D (central) vs. 1D (video);
- comparison temporal evolution of “global” variables (fluid temperature at outlet and average rock temperatures).

⬇

1D/1D (unsteady) model gives satisfactory results and it’s faster

Preliminary optimization of the GHS

Consider the initial simulation (Case A), we can compute the exergy efficiency as:

$$\eta_{ex} = \frac{\left(Ex^{out} - Ex^{in}\right)_{\text{discharge}}}{\left(Ex^{in} - Ex^{out}\right)_{\text{charge}}} = \frac{\sum_{i=1}^{N}\left(Ex_i^{out} - Ex_i^{in}\right)}{\sum_{j=1}^{M}\left(Ex_j^{in} - Ex_j^{out}\right)}$$

where:

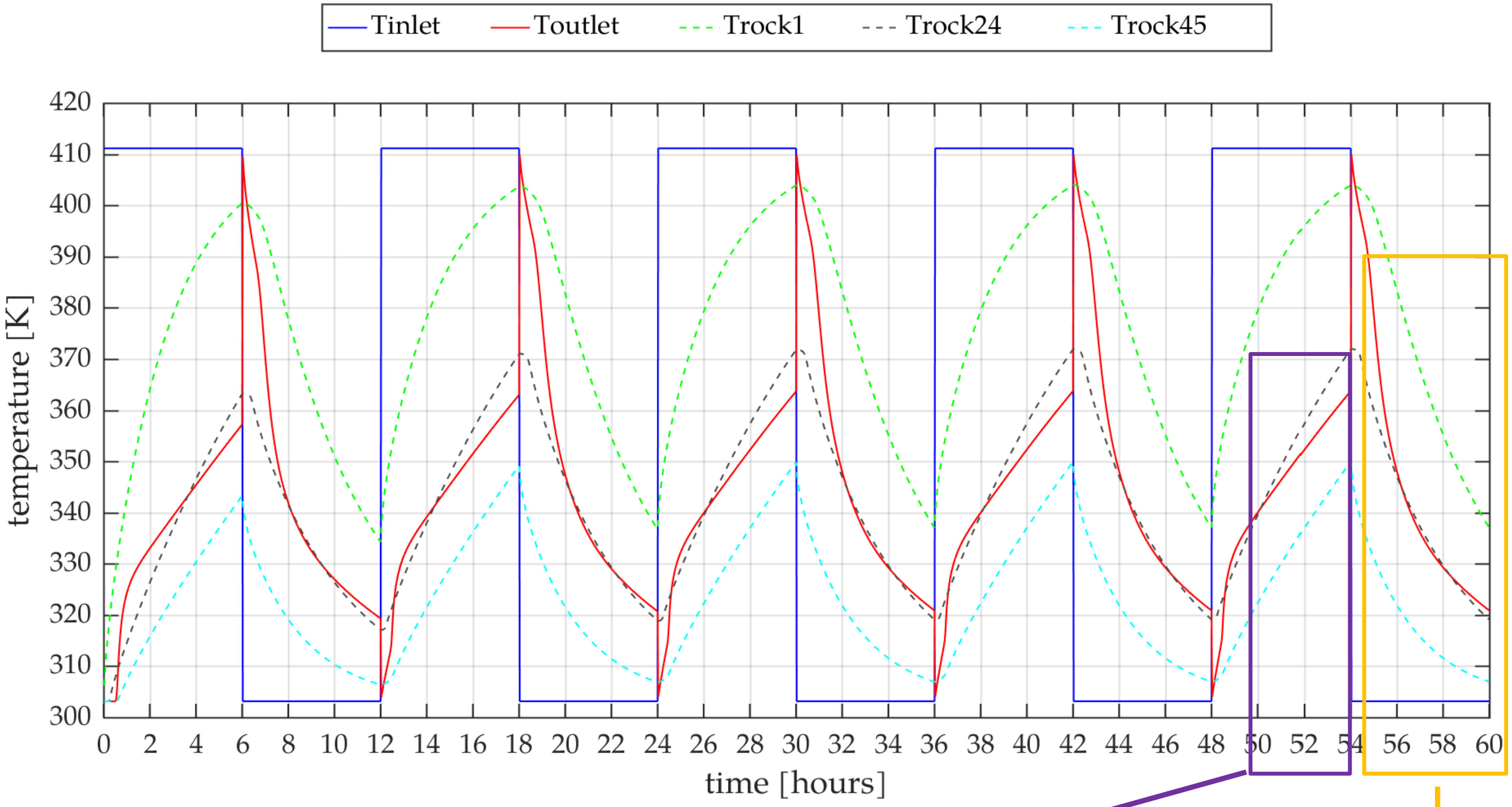
$$Ex_i^X = \left(\rho UA\right)_X \left[\left(h_X - h_0\right) - T_0\left(s_X - s_0\right)\right]\left(t_i - t_{i-1}\right)$$

cycle N°	**1**	**2**	**3**	**4**	**5**
η_{ex}	37.1%	46.4%	47.6%	47.7%	47.8%

→ **too low!!**

Preliminary optimization of the GHS

Results initial simulation (Case A)



charge: T_{outlet} too high

discharge: T_{outlet} too low

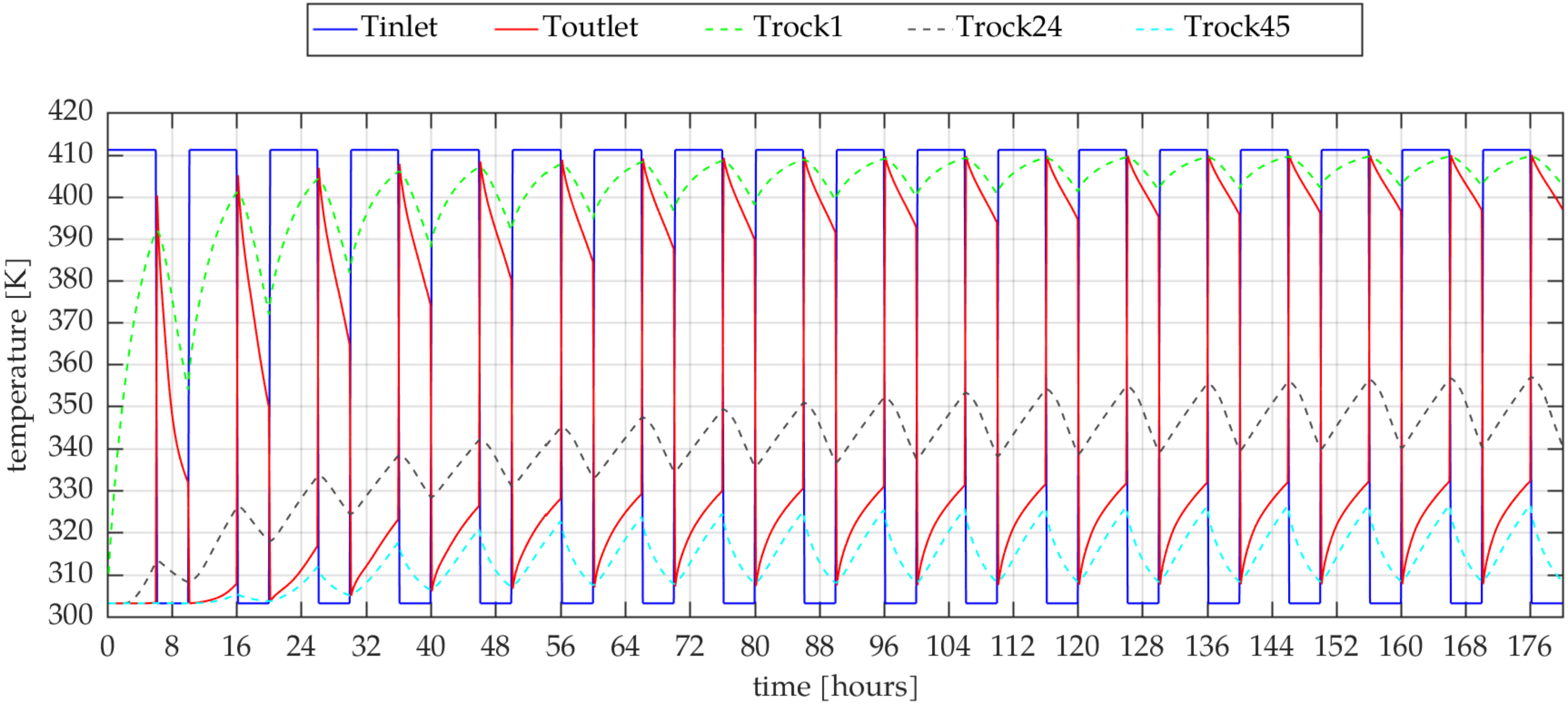
Preliminary optimization of the GHS

- Performed sensitivity analysis on the model parameters;
- Most important parameters are:
  - exchangers length;
  - mass flow rate;
  - charge & discharge duration;
- Run several simulations for optimizing the GHS (based on exergy efficiency and desired outlet temperatures);
- Final configuration (Case B):

	N° cycles	$\mathbf{L_{exch}}$ (m)	$\mathbf{t_{charge}}$ (hours)	$\mathbf{G_{charge}}$ (kg/s)	$\mathbf{t_{discharge}}$ (hours)	$\mathbf{G_{discharge}}$ (kg/s)
Case B	18	30	6	1.75	4	2.5

Preliminary optimization of the GHS

Evolution of inlet & outlet fluid temperature and volume-averaged rock temperatures



Preliminary optimization of the GHS

cycle N°	η_{ex} **(%)**		**cycle N°**	η_{ex} **(%)**
1	31.4		10	74
2	45.2		11	74.9
3	52.8		12	75.6
4	58.9		13	76.2
5	63.7		14	76.7
6	67.1		15	77
7	69.6		16	77.3
8	**71.5**		17	77.6
9	72.9		**18**	**77.8**

Conclusions and future developments

- developed and implemented two different models for the GHS;
- performed numerical tests and sensitivity analysis on the models:
    - quasi-steady flow assumption not correct => unsteady model must be used
    - faster 1D fluid /1D rock model can be used;
    - unsteady model accuracy is satisfactory even with very high Courant number;
    - determined most important model parameters;
- performed preliminary optimization of the GHS;

Ongoing work

- coupling of GHS model with thermodynamic cycles and ice storage models;
- experimental validation of the GHS concept and heat transfer measurements on a 1:10 prototype of a single exchanger.

Acknowledgments

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