The impact of surface roughness on heat transport in fractured rocks

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INTRODUCTION

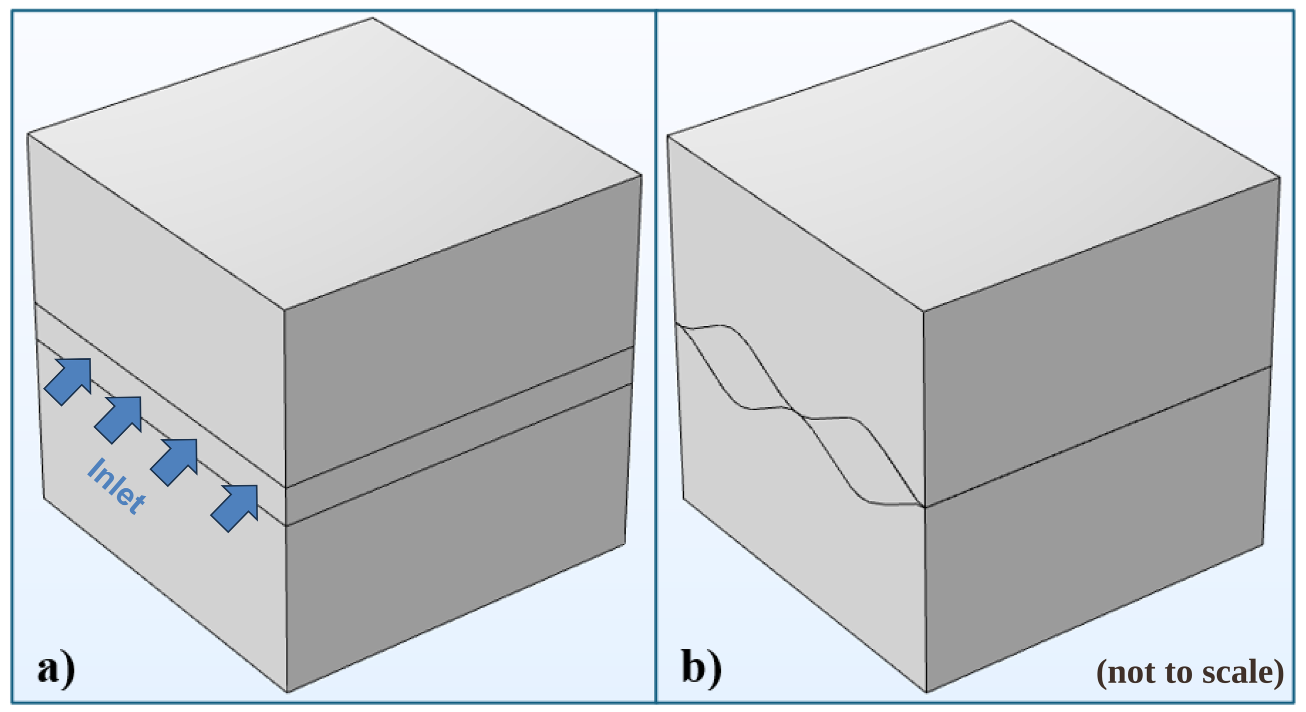
Understanding heat transfer in rock fractures is crucial for optimizing geothermal energy extraction, nuclear waste storage, and other subsurface engineering applications (Klepikova et al., 2016; Luo et al., 2016).

The roughness of the fracture walls can significantly impact heat transfer because the variability of aperture and shape promotes preferential paths for flow and advective transport ("flow channeling") and causes variation in the fluid-rock diffusive heat exchange. However, there is no clear consensus on the effects of flow channeling on the thermal exchange between the fluid and the rock matrix, as some authors observed a decrease, due to increased flow velocity and shortened transit times in the channeled regions (Neuville et al., 2010), while others report an increase, as radial conduction from the channel to the matrix is more efficient for heat transfer than the linear conduction occurring in a parallel plate model (de La Bernardie et al., 2018).

METHODS

- **Coupled flow & heat transport** ⟶ **COMSOL Multiphysics®** finite element-based (COMSOL, 2022)
- **3D domain — 1-meter cube**
- 2 types of fractures:

Planar | **Sinusoidal unmated**



- **Granite** (matrix) & **fractured granite** (fracture)
- ❑ **Aperture defined as a function in a 2D domain**
- ❑ **Cubic law**

Initial & Boundary Conditions

- **Inlet-outlet pressure gradient applied**
- **No-flow BC on remaining surfaces**
- **Outflow condition at the outlet**
- **Uniform initial temperature of 25°C**
- **1-hour 5°C cold pulse at the inlet**
- **Thermal insulation all other boundaries**

Solver Configuration

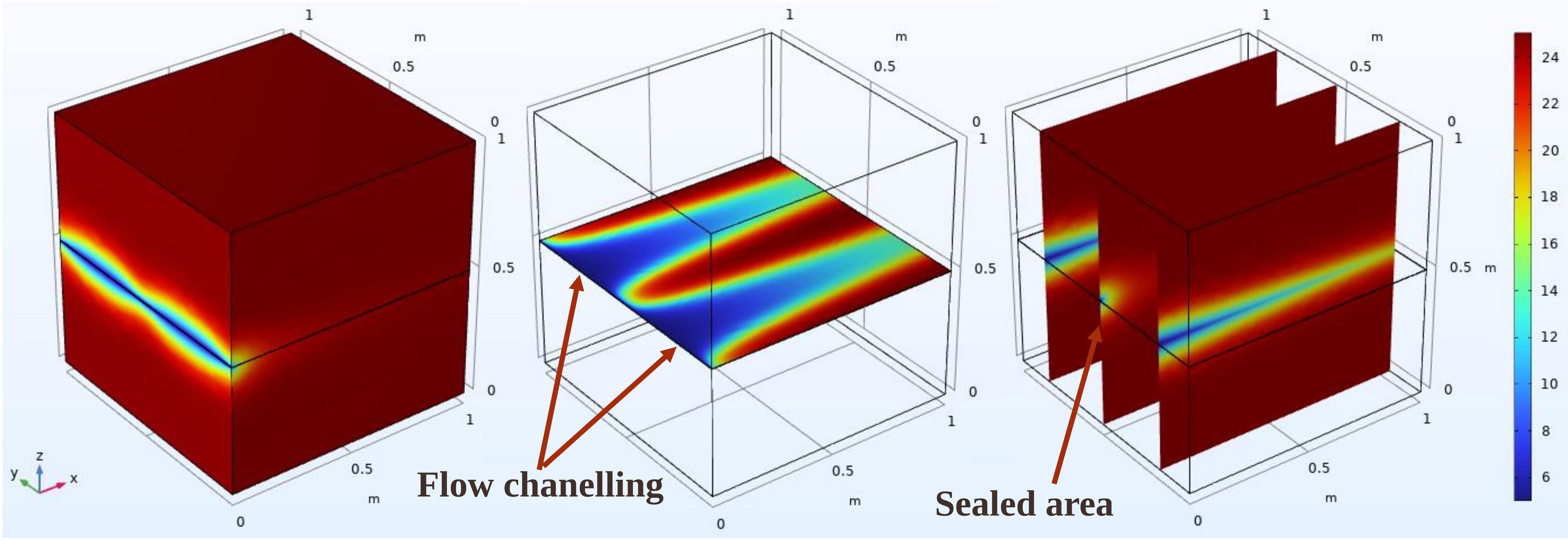
❑ Pressure and Temperature fields discretized using **first-order shape functions**

⟶ **Good balance** between **accuracy** and **computational cost**

❑ **Time-dependent** configuration: **100 hours** with **0.1 h maximum step constraint**

Heat propagates
- by **advection** through the **fracture**
- by **diffusion** through the **matrix**

RESULTS



Outlet Temperature Calculations

❑ **Average temperature** $N^{-1}\sum_i T_i$

❑ **Flow-rate weighted temperature** $\left(\sum_i q_i\right)^{-1}\sum_i q_i T_i$

$\boldsymbol{T_i}$ temperature
$\boldsymbol{q_i}$ flow rate
$\boldsymbol{N}$ 10^{-4} m intervals

Analytical Solution

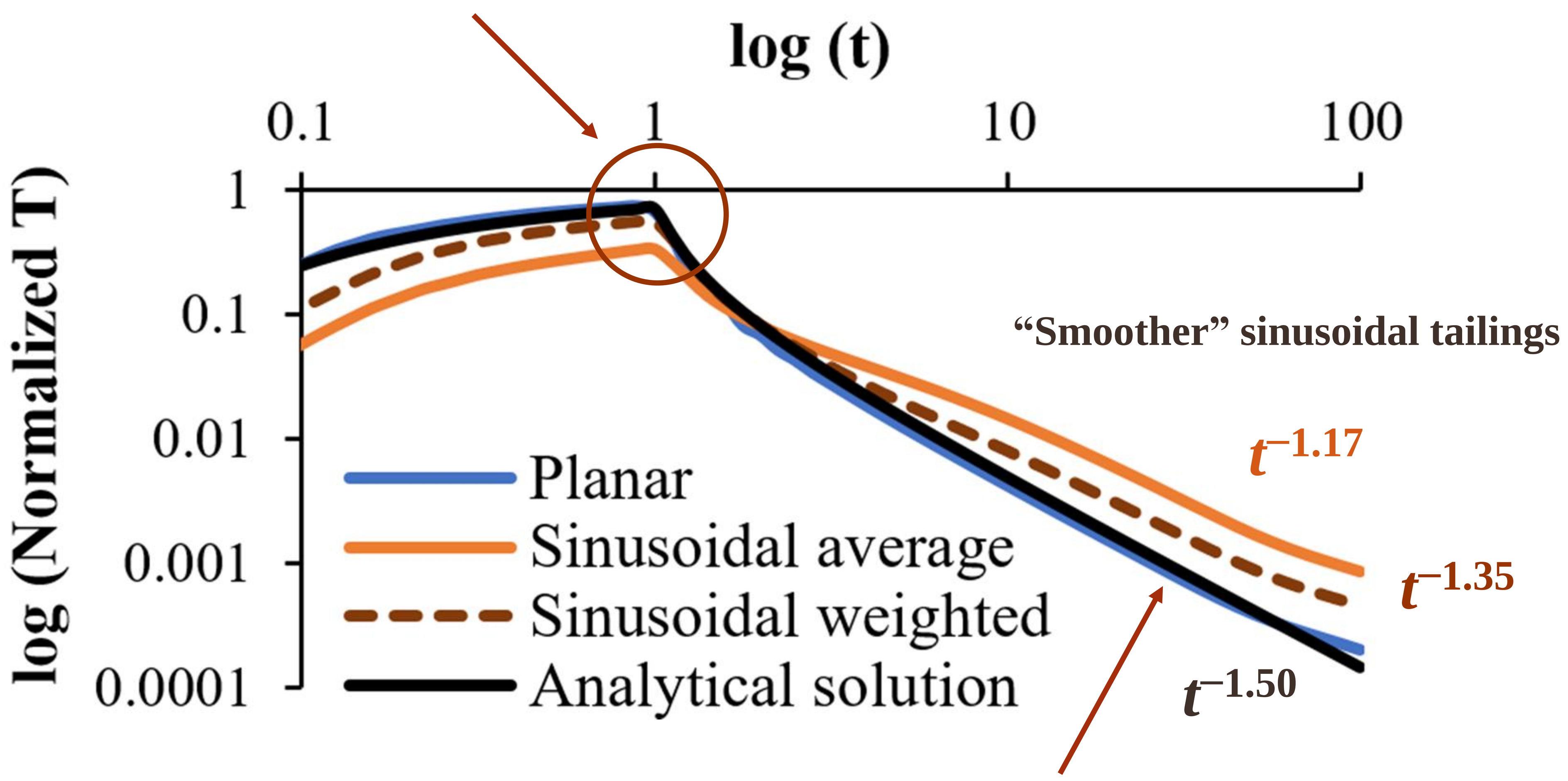
Cold pulse injection into a flat fracture over a defined time interval (Liu et al., 2007):

$$\Delta T = \Delta T_{inj} \cdot \mathrm{erfc}\left(\frac{\xi \cdot \sqrt{D} \cdot B}{2 \cdot \sqrt{(t-\tau)}}\right) \quad \text{for } \tau < t < t_{inj}$$

$$\Delta T = \Delta T_{inj} \cdot \left[\mathrm{erfc}\left(\frac{\xi \cdot \sqrt{D} \cdot B}{2 \cdot \sqrt{(t-\tau)}}\right) - \mathrm{erfc}\left(\frac{\xi \cdot \sqrt{D} \cdot B}{2 \cdot \sqrt{(t-\tau-t_{inj})}}\right)\right] \quad \text{for } t > t_{inj}$$

$\boldsymbol{T_{inj}}$ pulse temperature
$\boldsymbol{t_{inj}}$ time of injection
ξ matrix/fracture heat storage capacities
$\boldsymbol{D}$ thermal diffusivity
$\boldsymbol{B = \tau/d}$ flow wetted surface area
τ advective transit time
$\boldsymbol{d}$ fracture aperture

Higher peak temperature in planar model



Planar results consistent with Analytical Solution

CONCLUSIONS

✓ **Fracture roughness controls thermal response**

breakthrough curve tailings

- Sinusoidal: $t^{-1.17}$ (average), $t^{-1.35}$ (weighted)
- Planar: $t^{-1.50}$

⟶ Difference between models due to the variability in transit times and aperture (De Simone et al., 2023)

✓ **Numerical results fits Analytical Solution**

✓ **Peak outlet temperatures higher in planar model**

- *Consistent with other authors observations*

FUTURE WORK

- Explore 3D geometrically defined fractures to analyze the thermal behaviour when parallel plate assumption is not valid.

⟶ Previous studies (de La Bernardie et al., 2018) show that roughness can lead to t^{-1} thermal tailings, typical of cylindrical-shaped tubes.

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