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Tunnels, a new potential for sensible heat storage in rock: 3D numerical modelling of a reversible exchanger within tunnel

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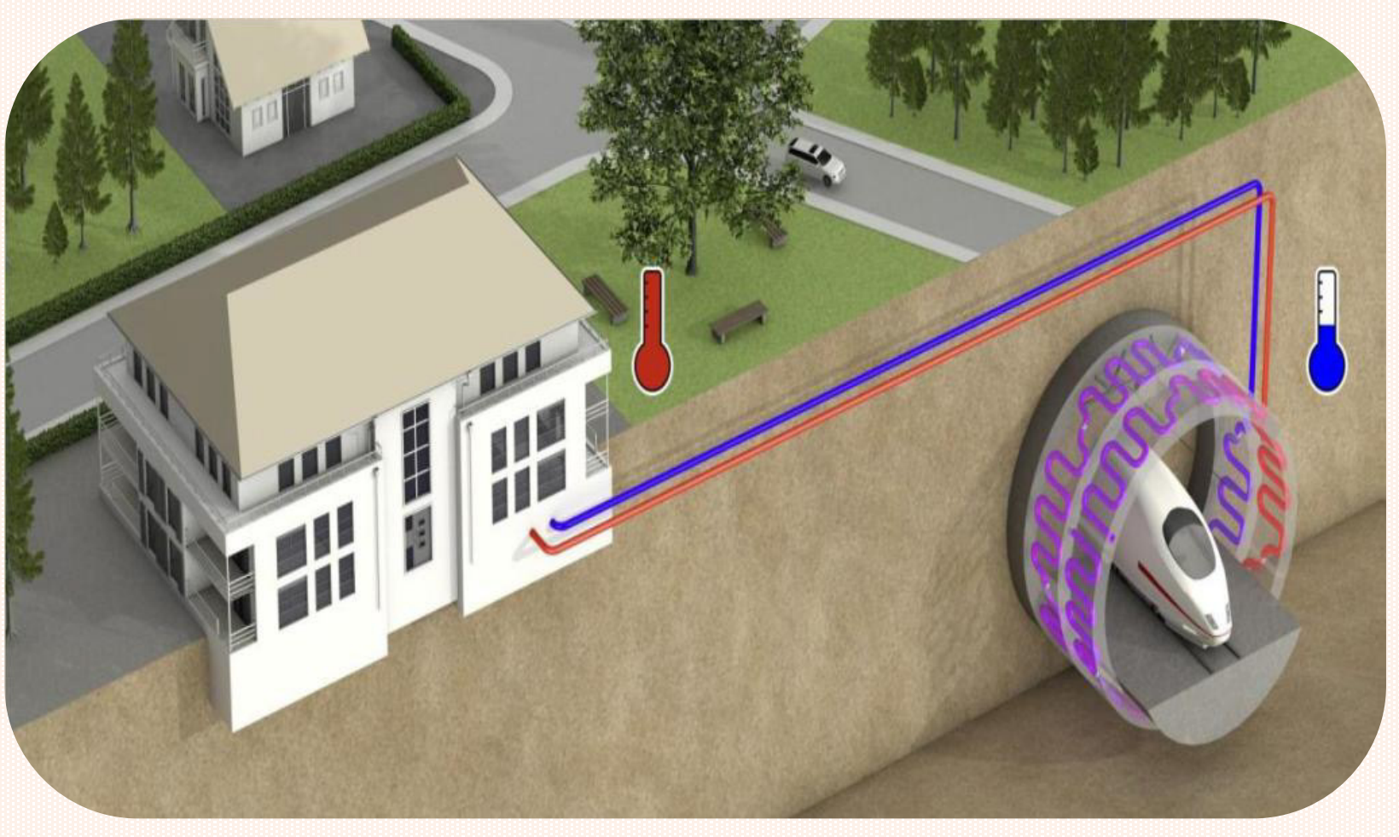
Introduction

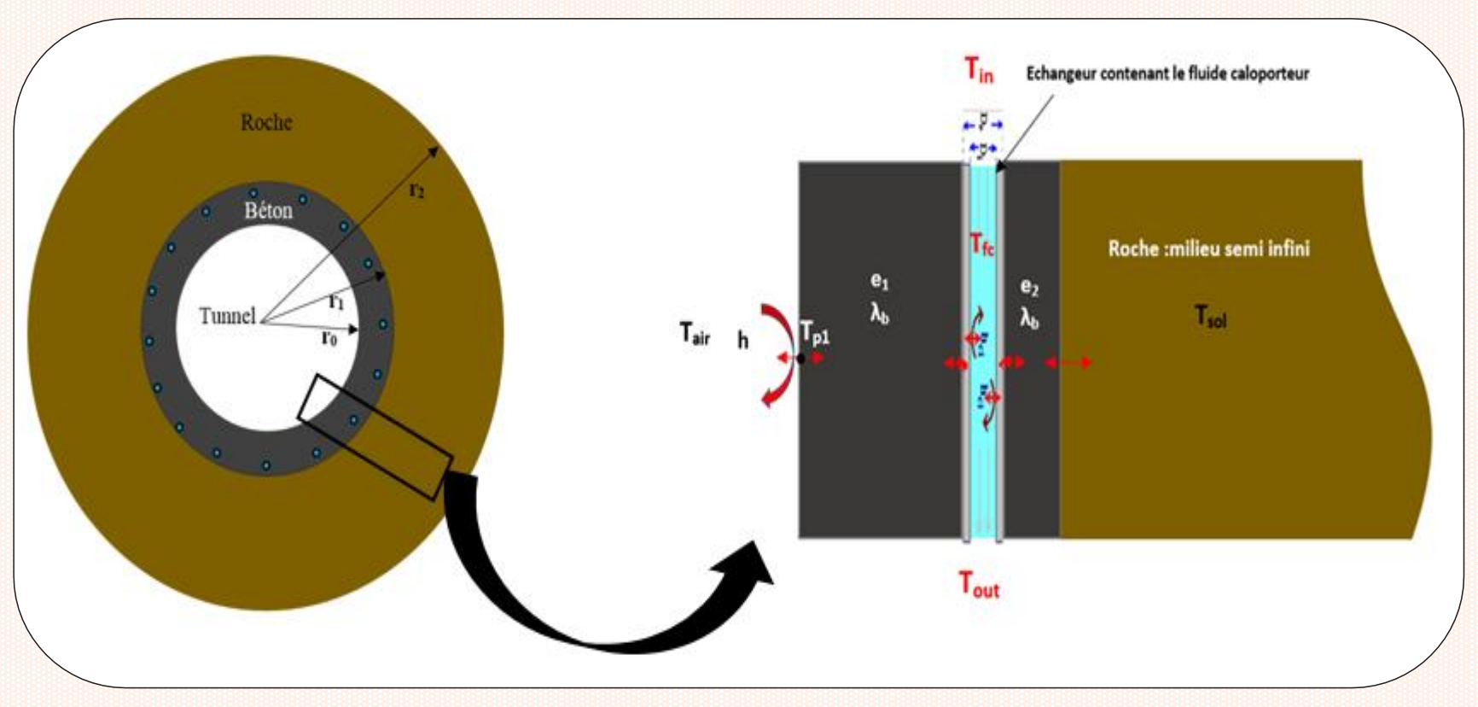
Existing urban tunnels constitute an interesting new opportunity to extract geothermal energy from the underground. This potential has motivated a research project, led by Ecole des Ponts, CNAM and Bouygues, is a part of the national program "*VILLE 10D – VILLE d'idées*" which was launched by the *Ministère de l'Écologie*, as proposed by the French Association of tunnels and underground structures (AFTES).

The objective is to estimate the thermal potential of the surrounding rock mass for inter-seasonal heat storage / recovery in the tunnel, using 3D numerical modelling. The model is used in a comparative and parametric study on the influence of fluid properties and ground thermal properties on the effectiveness of the exchange system and the thermal equilibrium of the surrounding soil or rock mass.

Principle

Pipes, witch are attached to the cage of prefabricated segments of the tunnel, are relayed by a heat pump (PAC). Heat exchange takes place between the pipes and the rock on one side, and the air inside the tunnel on the other side through the circulation of a heat antifreeze fluid.





In winter, the heat pump restores the heat collected to heat buildings on the surface, and the reverse operation in the summer (cooling).

Physics and equations

❖ **Transfer in porous medium**

Continuity equation $$div(\rho_w.u)+\frac{\partial \rho_w}{\partial t}=0$$

Darcy's law $$u=-\frac{K}{\mu}\nabla(p+\rho g z)$$

Heat transfert $$(\rho C_p)_{eq}\frac{\partial T}{\partial t}+\rho C_p u.\nabla T=\nabla.\left(\lambda_{eq}\nabla T\right)$$

❖ **Heat transfer in solid**

$$\rho C_p\frac{\partial T}{\partial t}=\lambda\nabla^2 T$$

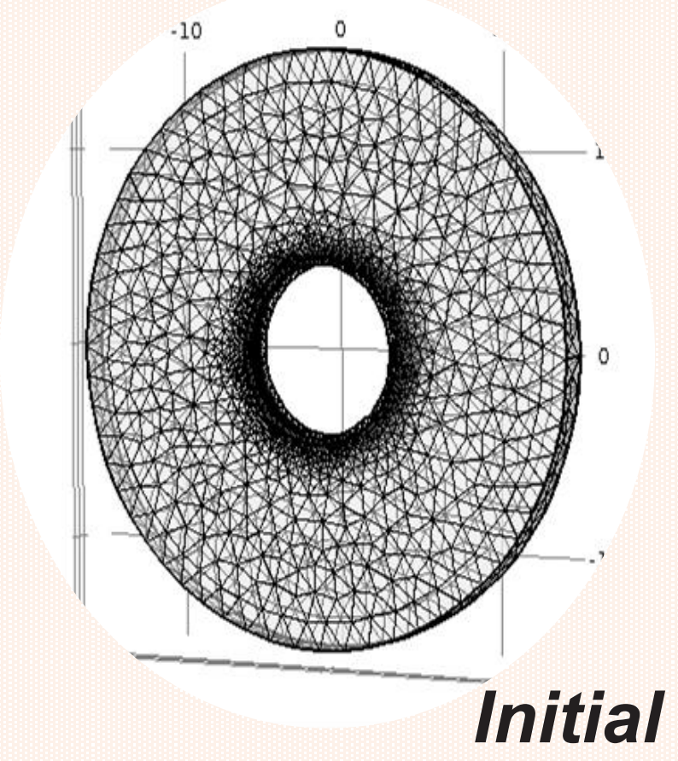
❖ **Heat transfer of a fluid in pipe**

$$\rho C_p\frac{\partial T}{\partial t}+\rho C_p u.\nabla T=\nabla.(\lambda\nabla T)+f_D\frac{\rho}{2d_h}|u|^3+Q_{paroi}$$

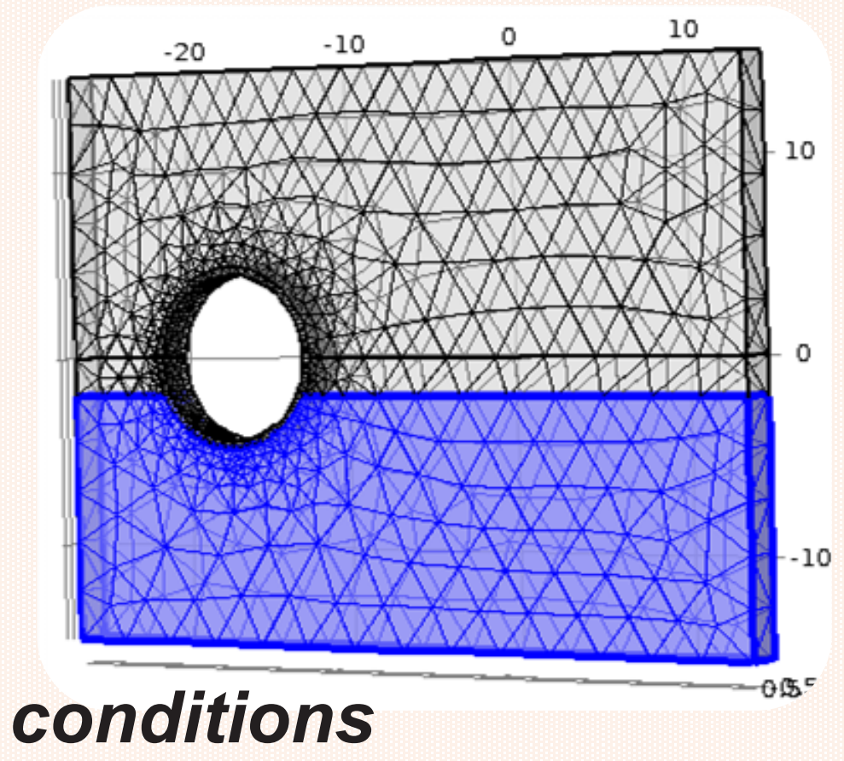
T : temperature
λ : thermal conductivity
ρ : density
C_p: thermal capacity
u: groundwater velocity
f_D: coefficient of friction

Numerical modelling and assumptions

Model without water table

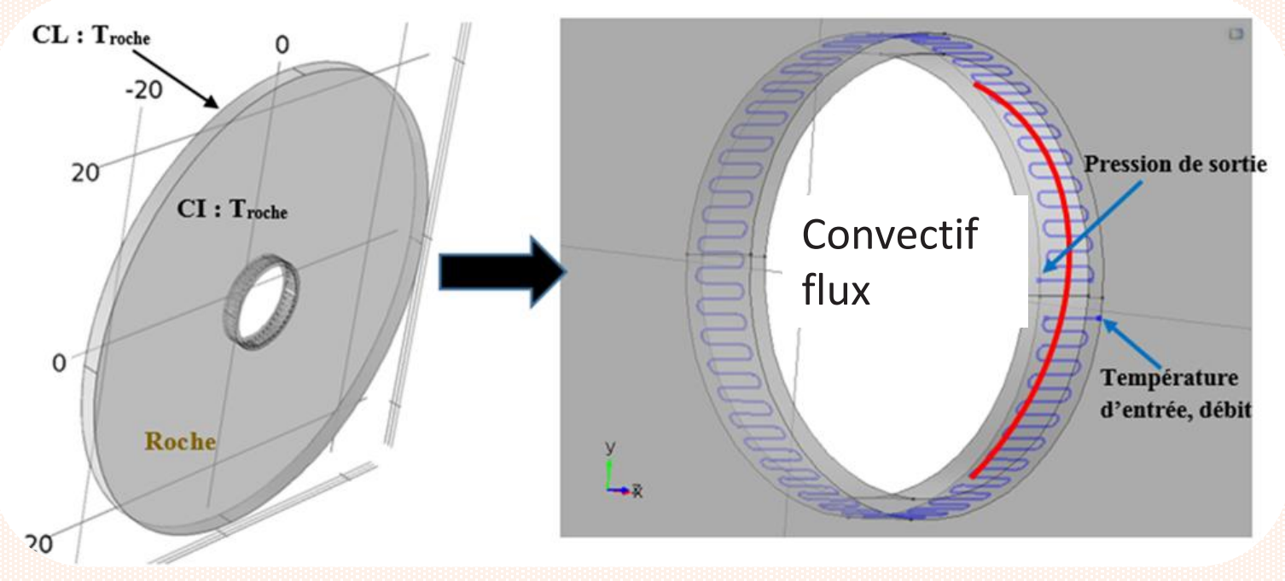


Model with water table



Initial / boundary conditions

- Rock's temperature T_{roche}
- Convective flow
- Inlet fluid's temperature T_{in}
- Fluid's flow rate
- Fluid outflow pressure
- Groundwater's velocity

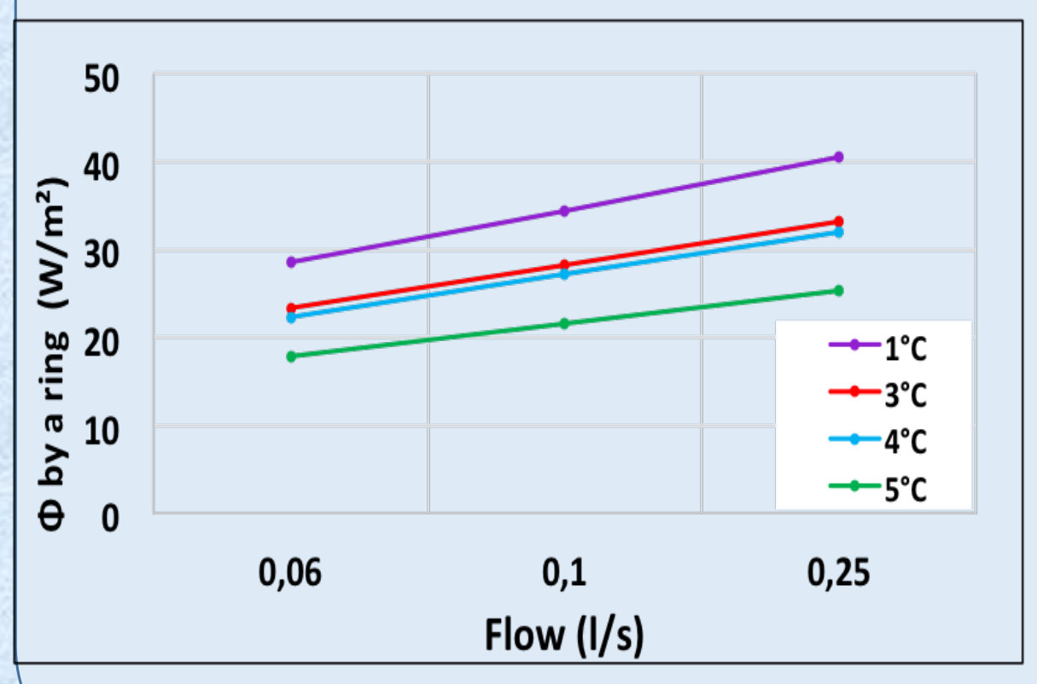


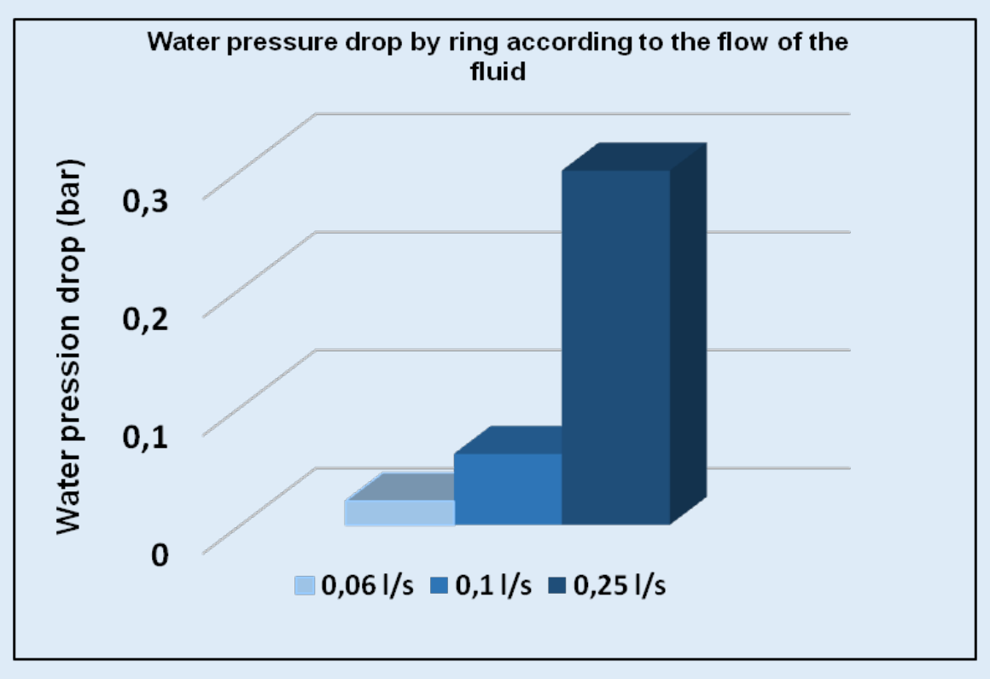
Results

Parametric analysis

The fluid's properties

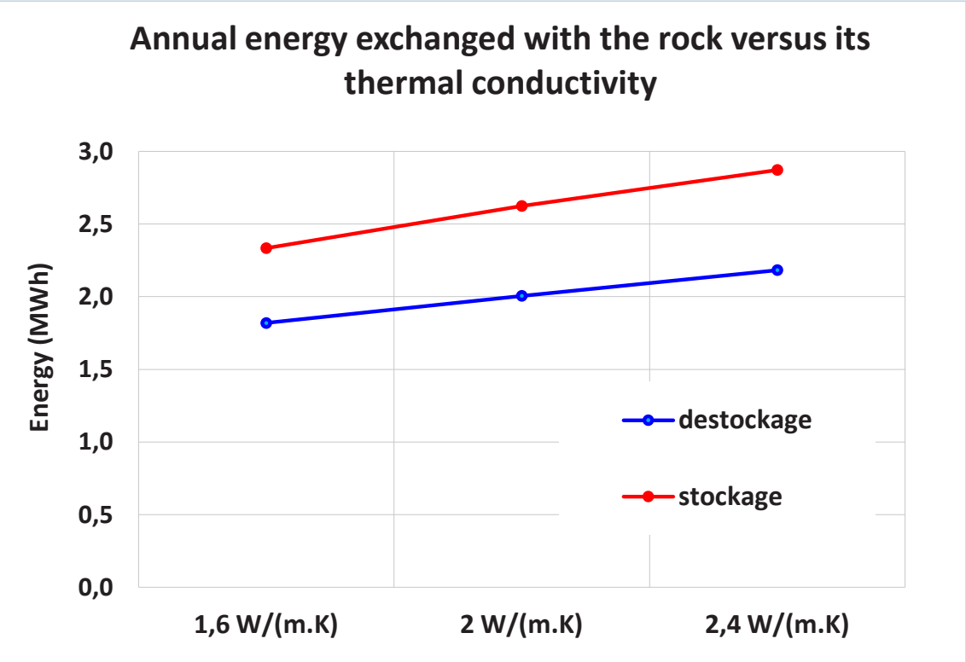
Calculation for 100 days in the heating mode

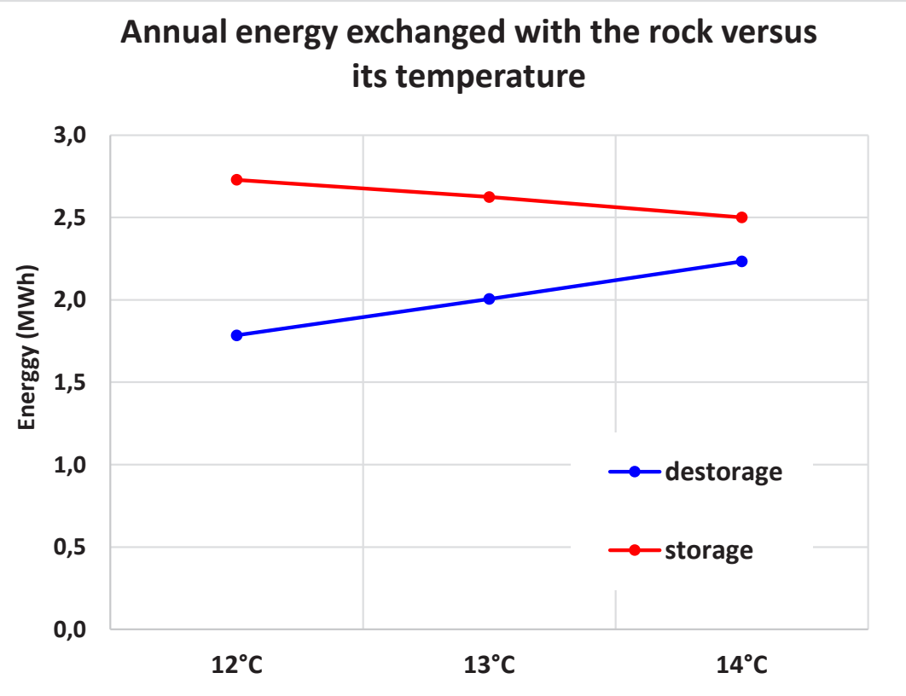




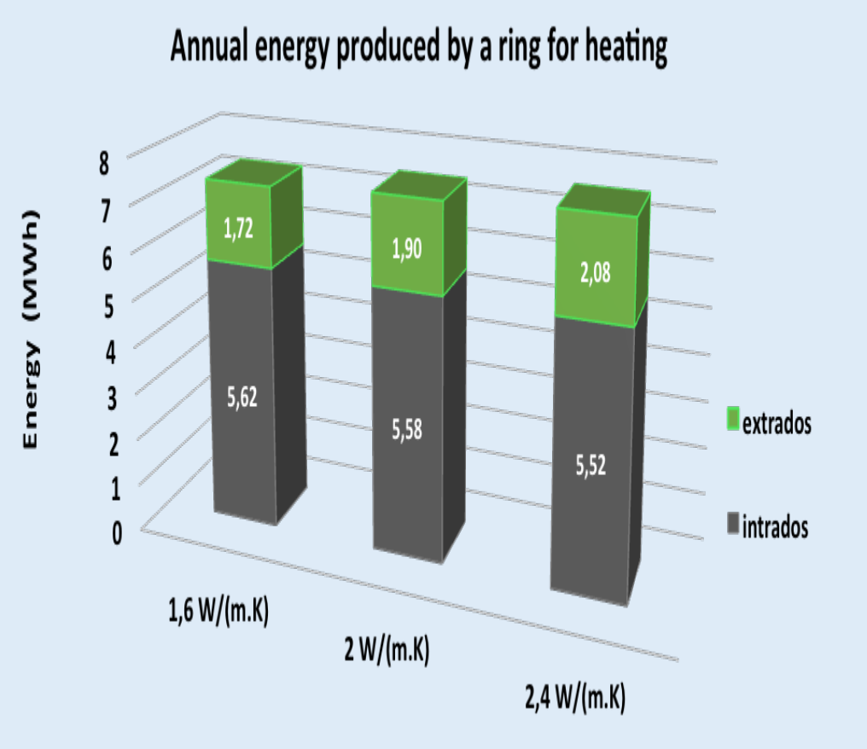
The rock's thermal properties

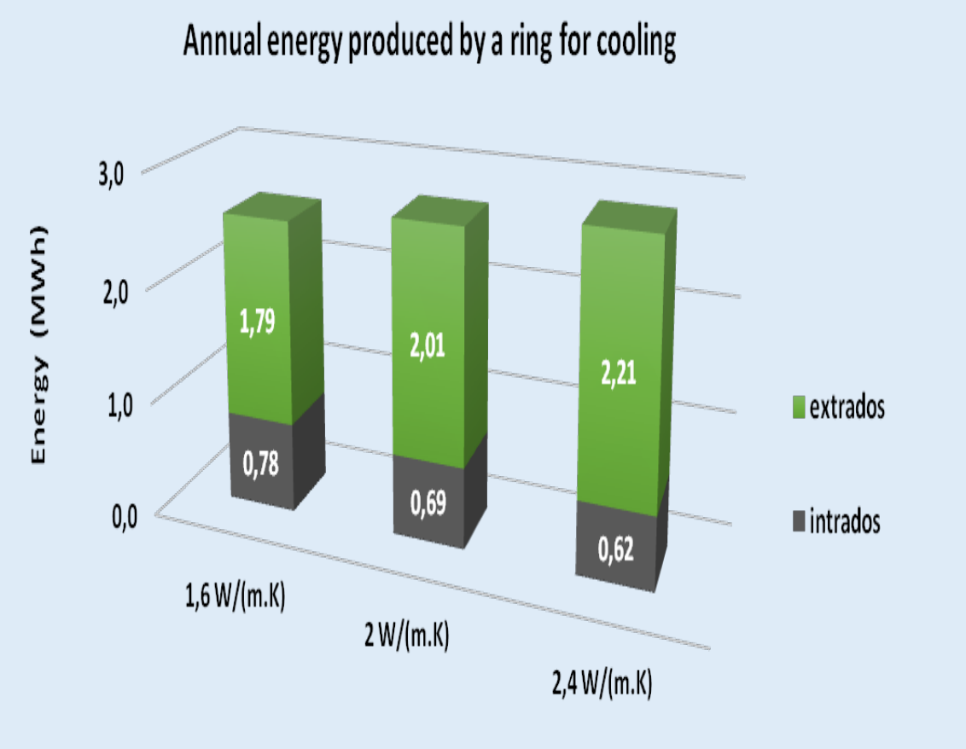
Calculation for 2 years of operation reversible





In winter, the thermal exchange is primarily done with the tunnel's air. In summer, the heat is injected into the rock.



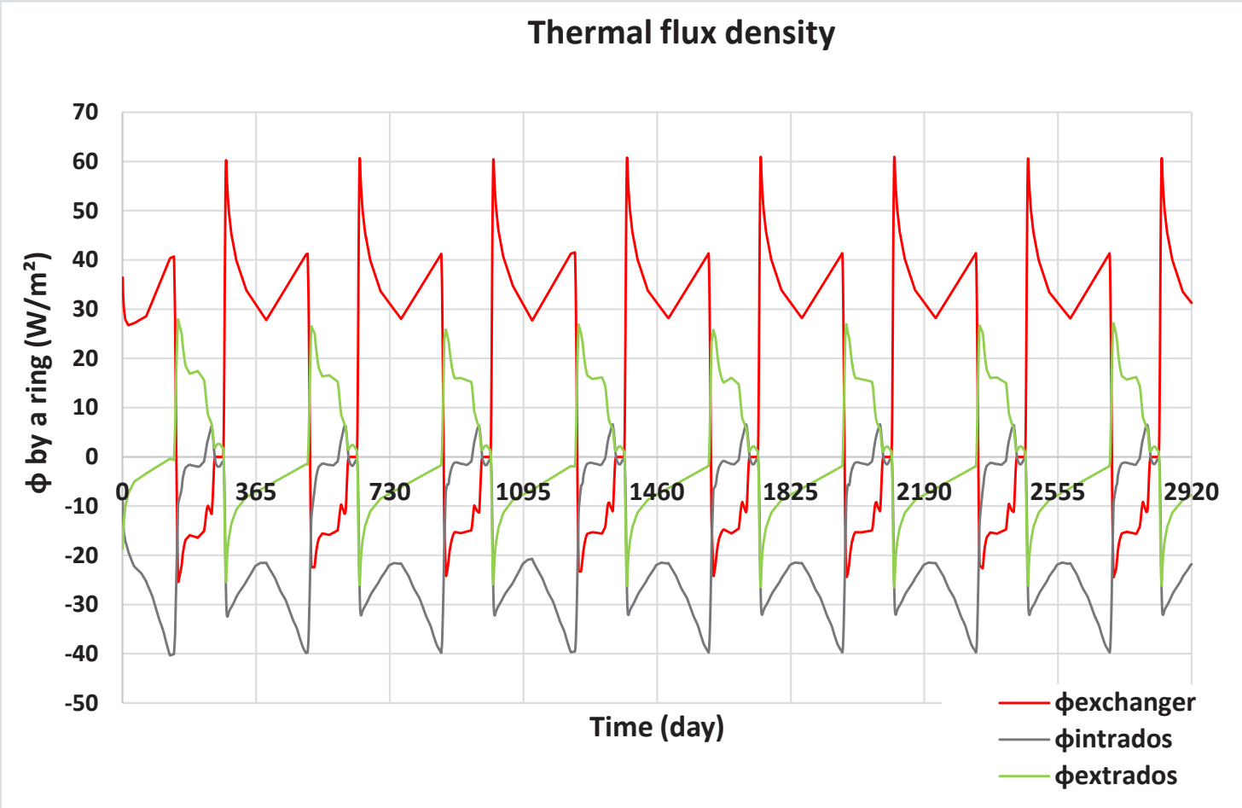


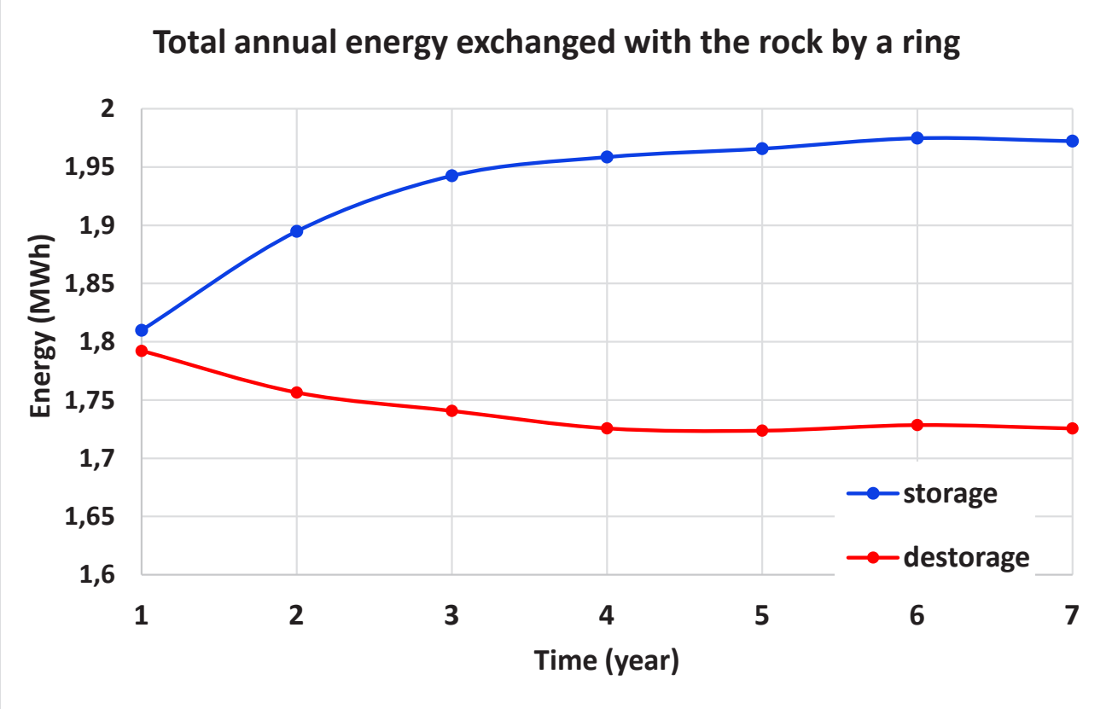
Sustainability of the system

Reversible operation

8 month heating + 3 month cooling +1 month break

The stored energy is larger in the winter time than in summer.



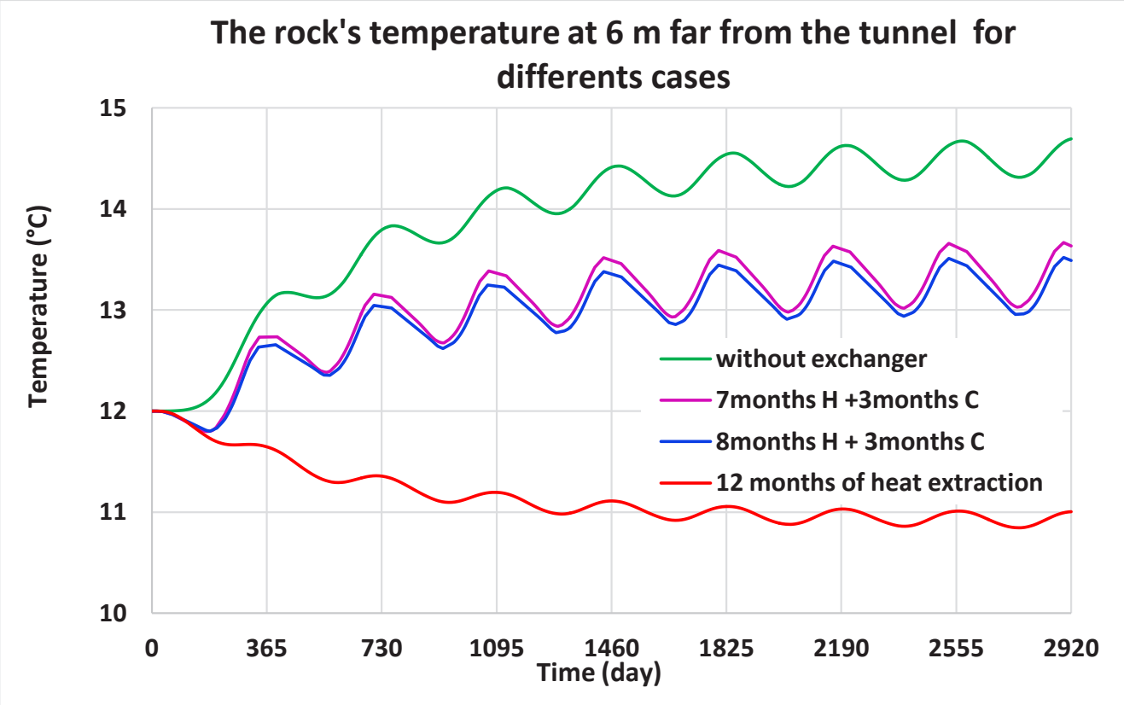


The amount of heat injected into the rock is always higher than that extracted from it.

Comparison between thermal activated and non-activated tunnel

The warming of the rock is due to the presence of the urban tunnel.

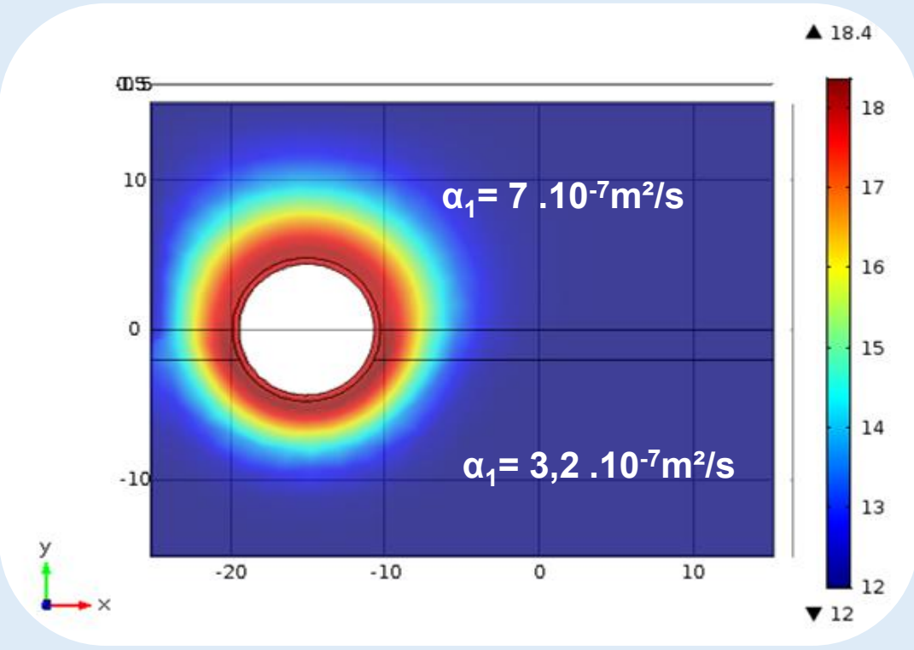
The exchanger system reduces thermal disturbances of the rock.



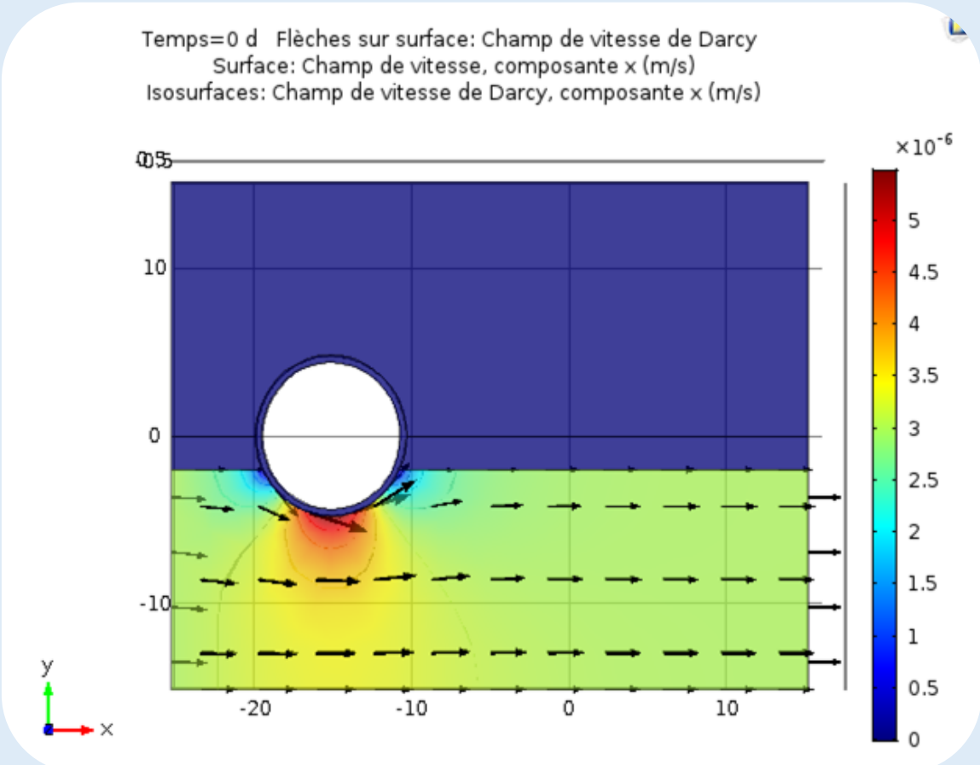
Effect of groundwater

Without groundwater flow

The zone of influence of the heat exchange system increases with the thermal diffusivity of the rock **α**.

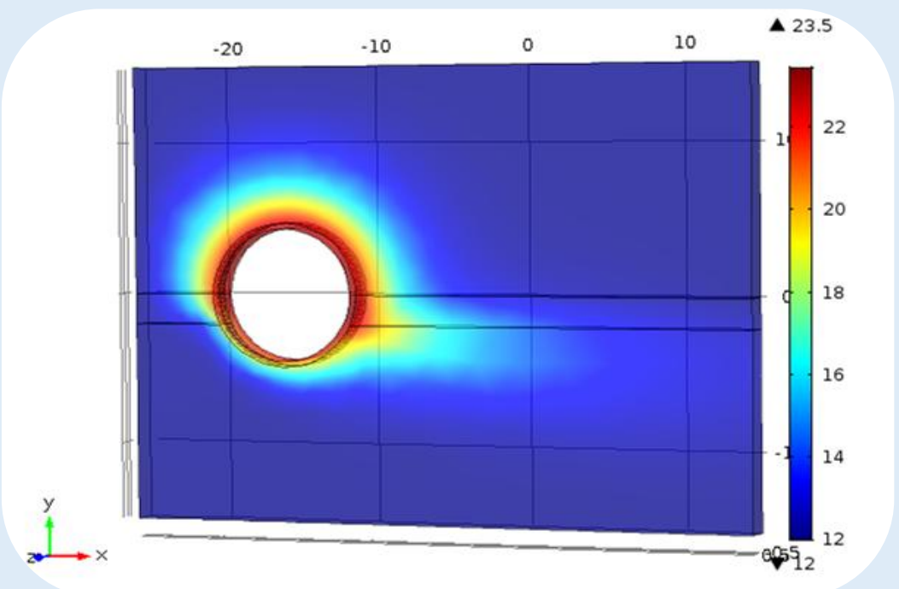


With groundwater flow

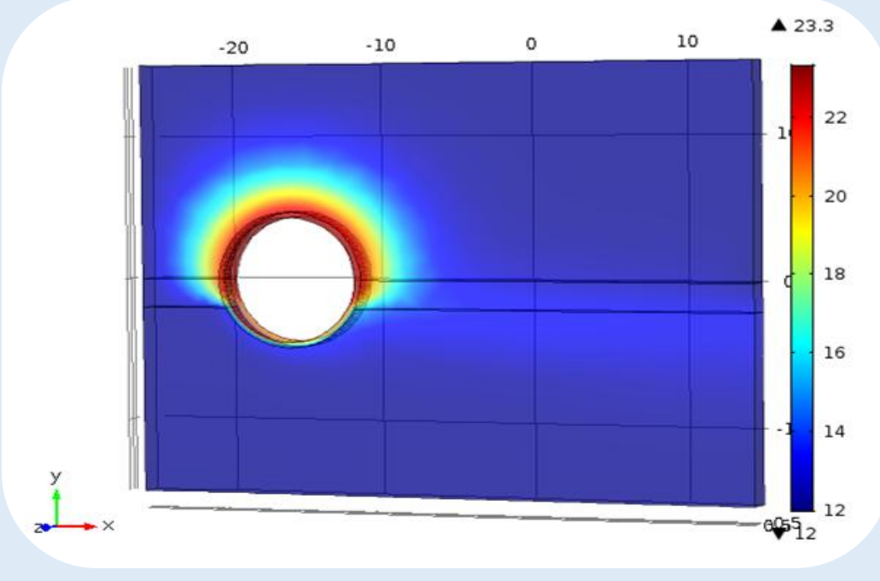


Non-uniform velocity field, determined by Darcy's law.

Groundwater transports heat and/or cold away from the tunnel. The rate of thermal recovery depends on groundwater flow velocity.



Groundwater's velocity 3.10^{-6} m/s



Groundwater's velocity 3.10^{-5} m/s

Conclusion

- Energy extraction from the tunnel has a positive environmental impact, as it reduces the thermal disturbance of the rock caused by the presence of an urban tunnel.
-The exchanger system performance is influenced by the fluid properties and to a lesser extent by the thermal properties of the rock in the absence of groundwater flow.
-The influence of the groundwater on the system increases with its flow velocity: In summer, it prevents heat storage in the rock near the tunnel so it can evacuate more heat and thus cool the building more efficiently. In winter, the flow renews the temperature therefore the exchanger extracts more heat from the rock. With low flow rates the general conclusions of the case without flow are applied.