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Thermo-Hydraulic-Mechanical (THM) Experiments and Numerical Simulations to Quantify Heat Exchange Characteristics of Fractured Limestone Reservoirs for Aquifer Thermal Energy Storage (ATES)

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ABSTRACT

A better understanding of heat exchange characteristics of fractured aquifers is of central interest for the development of Aquifer Thermal Energy Storage (ATES). In-situ aquifer testing and predictive modelling of heat transfer processes in fractured media should support such understanding.

In fractured limestone aquifer, the structures will control the flow geometry. At same bulk aquifer transmissivity, the flow geometry can differ significantly. The flow geometry influences contact area for heat transfer. Thus, it has a large impact on heat exchange properties of such kind of reservoir. In addition, to thermo-hydraulic processes, fractured media are also potentially strongly influenced by thermo-mechanical processes that in turn can affect the hydraulic characteristic of the aquifer. For example, thermo-elastic rock expansion in response to hot fluid injection could induce fracture closure and thus the transmissivity of the reservoir will decrease.

The practical implications for ATES development in fractured aquifer is that aquifer testing programs going beyond bulk hydraulic characterisation must be performed. At early project stage, only one well may be available and such information should be derived from single well testing protocols. For this purpose, we propose Thermo-Hydraulic-Mechanical (THM) experiments and numerical simulations in situations relevant for single well test. These include wellbore tests to quantify ambient flow and push-pull tests with heat and tracers. Push-pull tests of hot water or of tracers mix with variable reactivity with the in-situ rocks can be used to quantify the exchange capacity of a reservoir, which reflect the heat exchanger geometry. Borehole dilution test with continuous monitoring of concentration profiles can be used to evaluate ambient flow and flow partitioning. We present results experimental design in order to propose test parameters adapted according to various aquifer properties and well completion conditions. Thus, these results provide new insights on how to include Thermo-Hydraulic-Mechanical well test for characterized fractured limestone reservoirs.

1. INTRODUCTION

Energy transition turnaround has a main challenge today to face-off the global warming and the CO_2 emission. Geothermal energy storage is one of the key issue to the development of renewable energy. Many different technics are used in Underground Thermal Energy Storage (UTES) (Fleuchaus et al., 2018), but one of the most challenging concern the storage in deep hydrogeological layers, and the focus is steer to Aquifer Thermal Energy Storage (ATES). Until now many studies have shown the potential of ATES in shallow underground storage in porous geological media. But today the goal of many institutions is to go deeper to avoid any environmental harmful effect link to different kind of high temperature water injection and storage.

Thermal-Hydraulic-Mechanical (THM) experiments is primordial for management and fundamental research on fractured Aquifer Thermal Energy Storage (ATES). At early project stage, technical limitations of current industry standard well tests have strongly limited progress in understanding how heat exchange within dynamic aquifers.

General pumping tests is use to quantify hydrogeological conditions for underground storage sites. These tests are adequate for hydrodynamic characteristic of the aquifer (water flow, transmissivity, porosity, permeability, etc.). However, they do not allow the calculation on the potential of the aquifer for storing heat (volume of the rock heat exchanger), which hinder the development of ATES in fractured hydrogeological conditions.

Here, we introduce out a methodology to overcomes the above outline limitations and provide filed experiment plans and numerical simulations for its application to fractured limestone ATES.

2. METHODOLOGY

Limestones aquifers are generally fractured and karstified, which render difficult their structural understanding. Several studies have demonstrate the potential of classic well tests analyses and geostatistical geo-structure distribution as Discrete Fractured Network (DFN) or conduit distribution (Karst) network to design their underground shapes.

Unfortunately, the complexity of such systems make hard the prediction of the real form of the reservoir and almost impossible to quantify the possible volume of exchanger between fractured or karsified structures and the rock matrix.

The structures in the aquifer will control the flow geometry. At same bulk aquifer transmissivity, the flow geometry can differ significantly. This will have a large impact on heat exchange properties of the reservoir.

The methodology proposed is simple. We focus on the temperature that we can store in the reservoir via an injection test in satured condition and the thermal response of the push-pull experiment will allow us to determine experimentally and numerically, if the aquifer has the potential volume required considering simple structure (fractures or conduits) to store any heat demand (Fig.1).

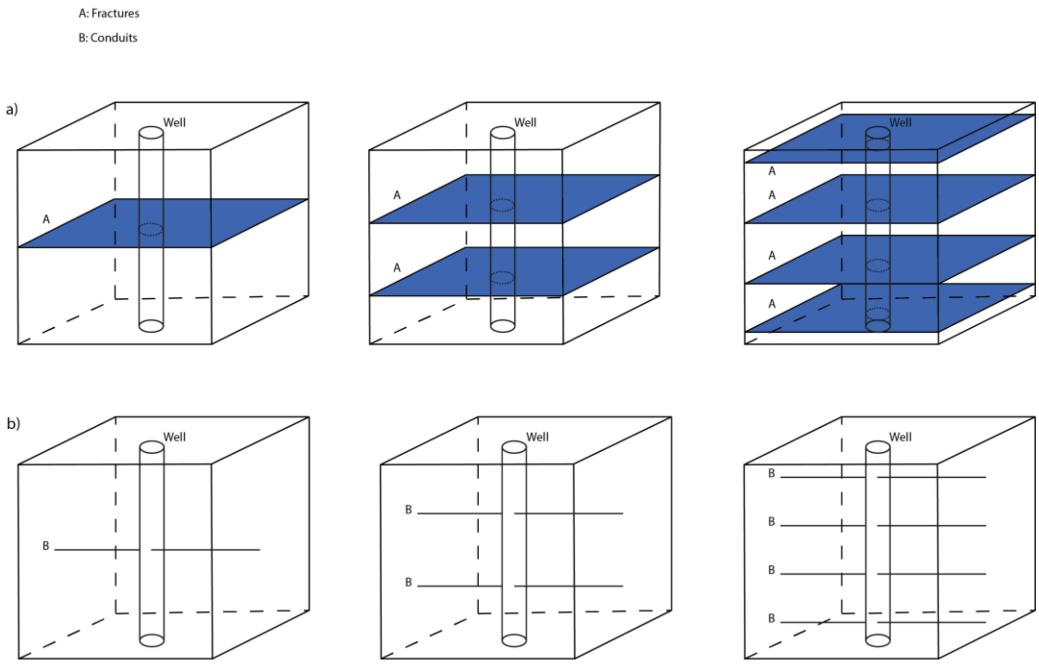

Figure 1: Simple conceptual model considering a) fractures network or in b) conduits network

The diffusion equation for a discrete fracture model that separately treats the processes occurring in the matrix form the processes occurring in the fractures has to be solved. Pressure diffusion of a slightly compressible single-phase fluid in a fractured reservoir is expressed for the two domains:

$$\frac{\partial p^m}{\partial t} = \frac{1}{\o^m \beta} \cdot \nabla \left[\frac{\kappa^m}{\mu^m} \nabla(p^m - \rho_f g)\right] + \psi^{mf} + Q^m \tag{1}$$

$$\frac{\partial p^f}{\partial t} = \frac{1}{\o^f \beta} \cdot \nabla \left[\frac{\kappa^f}{\mu^f} \nabla(p^f - \rho_f g)\right] + \psi^{fm} + Q^f \tag{2}$$

where superscript m refers to the matrix and superscript f refers to the fracture, p [Pa] is the fluid pressure, ø [-] is the porosity, β [Pa^{-1}] is the compressibility of both rock and fluid, κ [m^2] is the permeability, μ [Pa s] is the fluid viscosity, ρ_f [kg/m^3] is density, and g [m/s^2] is accerlation of gravity. The empirical flux transfer function ψ [Pa/s] accounts for fluid pressure exchange between the fracture and the matrix (Peaceman, 1978). Fracture permeability is adapted using two simplifications derived from the Kozeni-Carman law:

$$\kappa^f = \frac{a^2}{12} \tag{3}$$

$$\kappa^c = \frac{r^2}{8} \tag{4}$$

where a [m] is the fracture aperture and r [m] is the radius of the conduit. The cubic law (Eq. 3) derives from assuming parallel plates, and Equation (4) is the cubic-law equivalent for circular conduits. Note that κ^c is substituted for κ^f (in Eq. 2) when using the circular conduits shape.

We assume thermal equilibrium so that $T = T_r = T_f$, where T_r and T_f are the temperatures of solid rock and fluid respectively (Nield & Bejan, 2006). The heat transport equation is derived similarly to the pressure equation by balancing the heat transport mechanisms.

The heat transport equation is separated into matrix and fracture parts according to the same procedure as for the fluid pressure equation, if local thermal equilibrium is assumed.

$$\overline{c_p \rho}^m \frac{\partial T^m}{\partial t} + (c_p \rho_f \boldsymbol{v})^m \nabla T^m - \bar{\lambda}^m \nabla^2 T^m = \bar{q}^m + X^{mf} \tag{5}$$

$$\overline{c_p \rho}^f \frac{\partial T^f}{\partial t} + (c_p \rho_f \boldsymbol{v})^f \nabla T^f - \bar{\lambda}^f \nabla^2 T^f = \bar{q}^f + X^{fm} \tag{6}$$

where the heat capacity c_p [J/kgK], the thermal conductivity λ [W/mK] and internal heat source q [W/m^3] of solid rock and fluid. The fluid velocity v used in the heat transport equation is the Darcy velocity. The over-lined properties denote volume averaged mean values for the porous medium. X^{mf} and X^{fm} are the heat transfer function between the matrix and the fractures.

2.1 Experiments

The first ATES experiment was performed by the Centre for Hydrogeology and Geothermics (CHYN) at the University of Neuchâtel (Switzerland) in 1974 (Saugy et al., 1984; Saugy et al., 1992; Tsang & Hopkins, 1982), followed by a three-stage experimental project at Auburn University (USA) in 1976 (Moltz et al., 1978; Moltz et al., 1979; Moltz et al., 1983; Tsang et al., 1981). Further countries such as France, Japan, Germany, or Canada started participating in ATES research with their own experimental field sites.

Here, the idea is to perform, on a new experimental test site in Concise (VD) Switzerland (Fig. 2), thermal push-pull test during several days and see the response of the thermal plume within the withdrawal curves for all different tests.

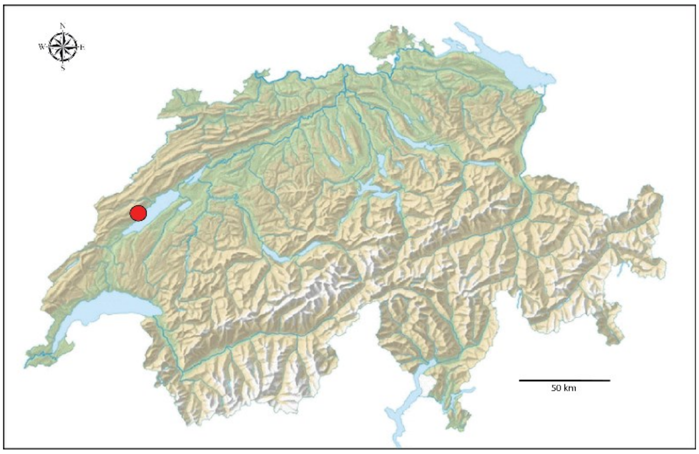

Figure 2: Location of the new experimental test site of the Centre for Hydrogeology and Geothermics (CHYN), in Concise (VD), Switzerland.

Hot fluid injection will induce a thermo-mechanical response of the rock that in turn can impact the hydraulic characteristic of the aquifer. For example, thermo-elastic rock expansion could induce fracture closure (Fig. 3) and thus the transmissivity of the reservoir will decrease. It is required to measure the mechanical conditions in the reservoir (e.g. stress state) in order to assess the impact of such effects on an aquifer thermal storage system.

The thermal response will be different considering granular, fractured or karstic rock. Comparing with different numerical simulations, we will be able to design the geo-structure in the vicinity of the well. These underground morphology will allow us to determine the volume which can be identify for any heat storage potential considering local hydrogeological conditions.

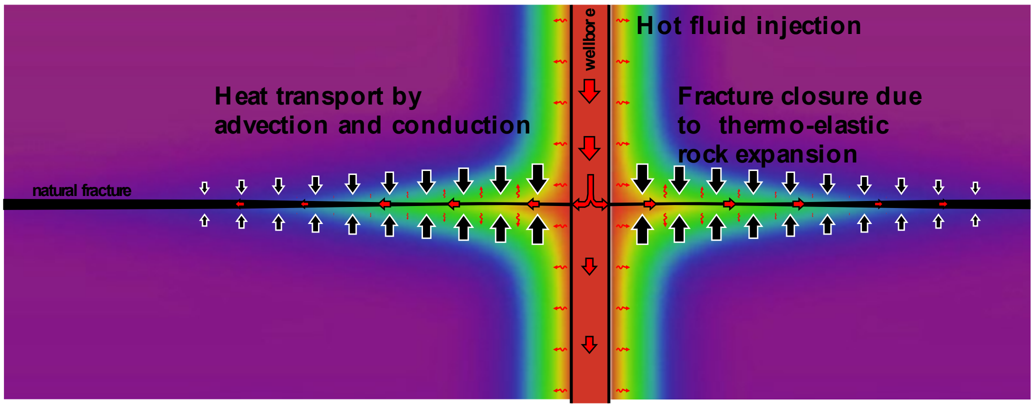

Figure 3: Schematic representation of fracture closure in response to hot water injection.

2.2 Numerical simulations

The approach is to use numerical simulations and in-situ well tests in order to:

1) Define the relevant key aquifer parameters that must be determined to provide reliable heat storage design in fractured aquifers;
2) Propose well testing approaches (single well configuration) that can be deployed to estimate these key aquifers parameters;

3) Assess the feasibility of these testing approaches through numerical simulations and field tests;

4) Provide testing protocols, simplified test design guidelines and application examples in order to support the acceptance of these testing approaches as an industry standard for heat storage project development in fractured aquifers.

Numerical simulations will help to design test protocols. Here as an example, we show with a 2D simple case that injecting hot water (50°C) and pumping in a reservoir (15°C), with same rock properties, but with two different scenarios of geo-structures, can have two different issues as expected by our approach.

The model set-up consists of a 100m wide, 50m thick in a hydrostatically-pressured fractured media. Both have a rock permeability of $k_m = 1e^{-17}$ [m^2] and fracture permeability of $k_f = 1e^{-9}$ [m^2]. The hydrogeological properties are in both examples the same. The only difference is that on Fig. 3, one geo-structure (1 fracture of 1mm thickness) is presented and on Fig. 4, nine geo-structures (9 fractures of 1 mm thickness) are designed.

The first case which is poorly fractured/karstify (1 fracture or 1 conduit) (Fig. 3) will have a tendency to not render the entire heat injected in the aquifer because of the low transmissivity of the rock matrix during the pumping stage (Fig. 3b). However, the second case which more fractured/karsify (9 fractures or 9 conduits) (Fig. 4) will be able to recover almost the entire heat injected into the aquifer with nearly any heat lost in the rock (Fig. 4b). The global rock transmissivity of the reservoir act as a heat exchanger where the volume of the geo-structure play a major role in storage capability and release. It is highly attractive to apply modelling concepts which harmonise with existing data and field test.

These simulations just highlight that the storage capacity is linked to interface with any geo-structure shape of the underground. This is why after several tests on our local site, we will be able to get a first estimation of the geological structures and calculate the possible storage amount in fractured limestone. This approach may be seen as a compromise between analytical and numerical model concepts as a verification of any fracture network models.

Quantifying the real form of this geology will help for fast decision making when only a single well is available at the starting of any heat storage project.

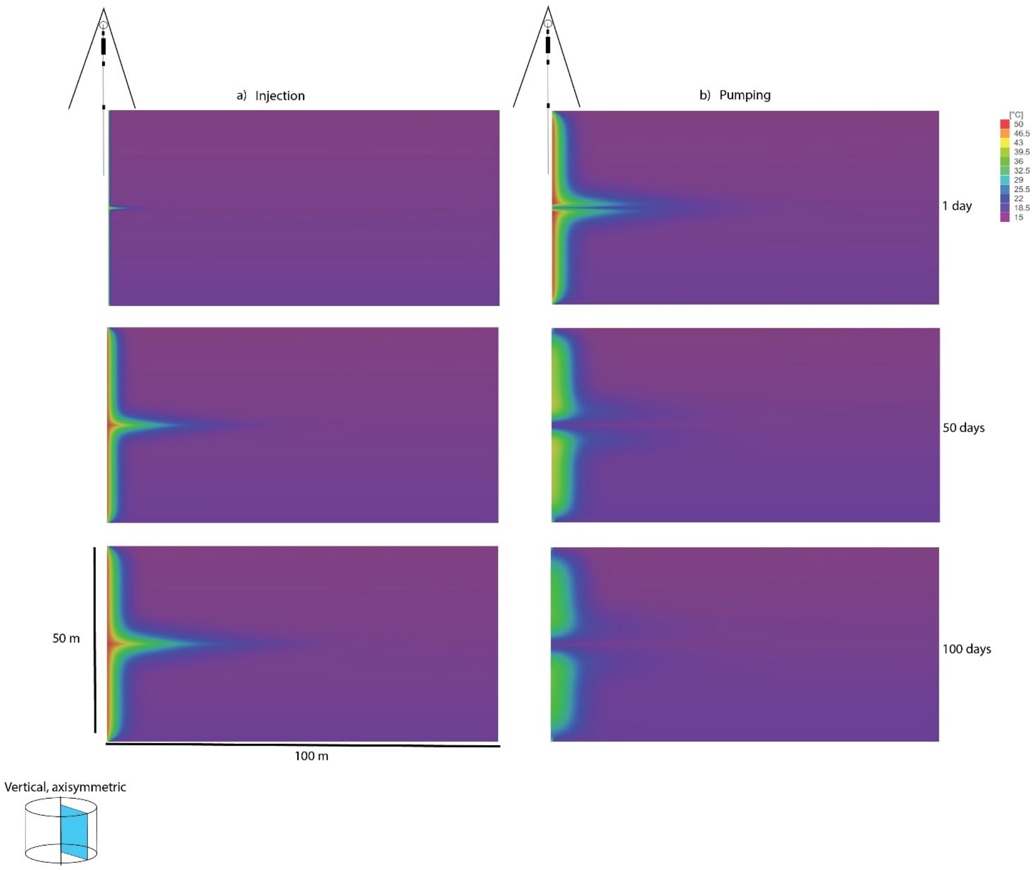

Figure 3: Numerical simulations of 100 days a) hot water (50°C) injection and pumping in a reservoir with an initial temperature aquifer at 15°C with 1 fracture.

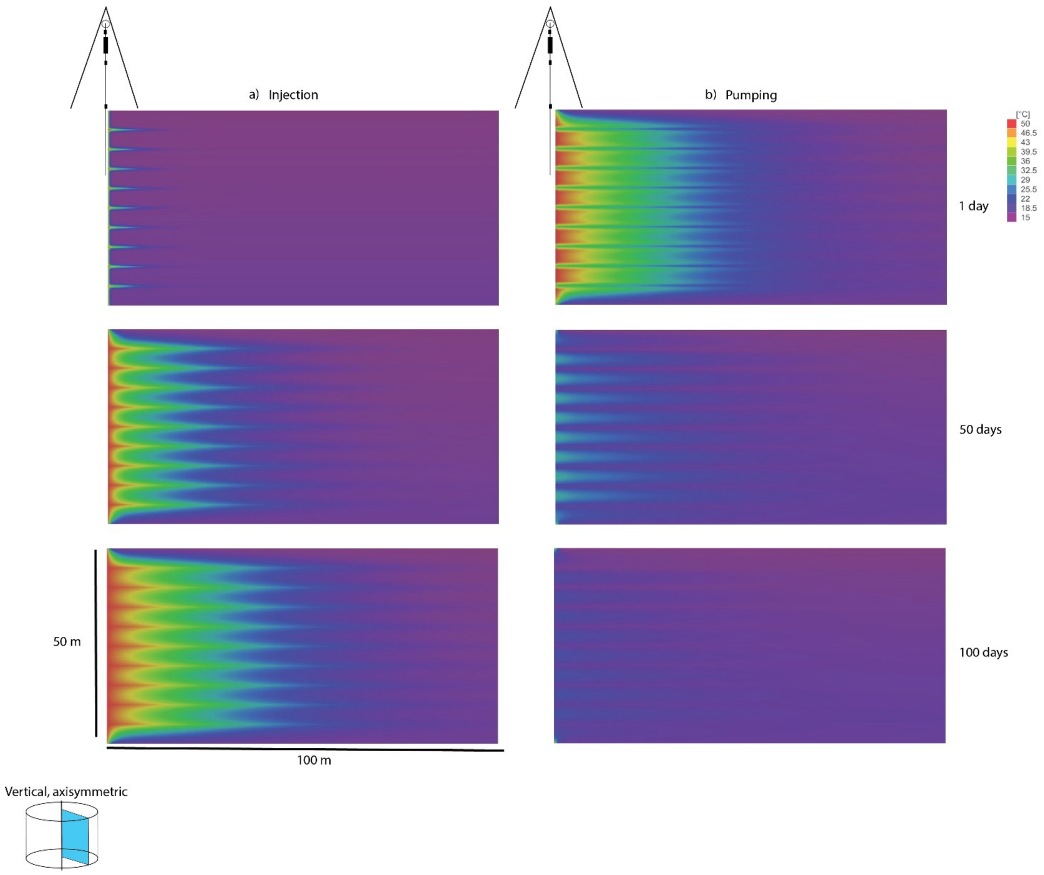

Figure 4: Numerical simulations of 100 days a) hot water (50°C) injection and b) pumping in a reservoir with an initial temperature aquifer at 15°C with 9 fractures.

3. CONCLUSION AND OUTLOOK

This research for Thermo-Hydro-Mechanical (THM) test in fractured/karstic rock will develop next generation ATES experimental and modelling tools required to address demands of scientists, engineers and regulators for Heat Storage Projects. This method include simple approach to make the link between storage capacity and real storage underground possibilities. The research will provide improved approaches to quantify system connectivity, complex geo-structure, hydrogeology and storage volume, based on physical experiments.

Advances from the programme include:

- Transport parameters
- Reactivity of the environment on the physical features on the experimental site
- Water tracing and residence times
- Flow measurements and hydraulic: efforts to characterize and model flows at various scales will also be pursued.
- Hydrogeophysical monitoring: new methods coupled with hydrogeological measurements (pressure, tracing, etc.) and geophysical measurements (electrical, etc.).
- Coupling of measurements and numerical modelling: in parallel with the acquisition of these data.

Computational studies should be undertaken as part of the various activities being conducted to improved Thermo-Hydro-Mechanical (THM) tests in fractured/karstic rock. This will allow for most robust predictions of heat storage characterization, reservoir performance and field site management. Our new simple approach seek to serve the needs of the Aquifer Thermal Energy Storage (ATES) in fractured/karstic media for the next projected years. It will be dedicate to overcome inefficiencies and accommodate flexible storage volume in limestone reservoir.

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