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Experimental investigation of heat transport through single synthetic fractures

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Abstract

A laboratory physical model has been set up to analyze heat transport dynamics through single synthetic fractures. The Synfrac program together with a 3d printer have been used to build several fracture planes having different geometrical characteristics that have been moulded to generate concrete porous fractured blocks. The tests regard the observation of the thermal breakthrough curves obtained through a continuous flow injection in correspondence of eight thermocouples located uniformly on one of the fractured blocks.
The physical model developed permits to reproduce and understand adequately some features of heat transport dynamics in fractured media

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Keywords: heat transport; fractured media; physical model

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1. Introduction

In fractured geothermal reservoirs, heat transport is highly influenced by the presence of the fractures, so appropriate knowledge of heat transport behavior in fractured aquifers is essential for accurate prediction of the heat dissipation and recovery from geothermal reservoirs.

Nomenclature

b	half aperture of the fracture (L)
B	half fracture spacing (L)
c_w	specific heat capacity of the water ($L^2T^2K^{-1}$)
c_m	specific heat capacity of the matrix ($L^2T^2K^{-1}$)
δ	Thickness boundary layer (L)
D_f	Thermal dispersion coefficient (L^2T^{-1})
k_e	Effective thermal conductivity of the matrix ($MLT^{-2}K^{-1}$)
L	Length of fractures (L)
ρ_w	Density of the water (ML^{-3})
ρ_m	Density of the matrix (ML^{-3})
Re	Reynolds number
t	time (T)
T_f	Temperature of fracture (K)
T_m	Temperature of matrix (K)
TRA_{eq}	Equivalent transmissivity (L^2T^{-1})
u_f	Thermal convective velocity (LT^{-1})
x	Coordinate parallel to the axis of fractures (L)
z	Coordinate perpendicular to the axis of fractures (L)

The study of heat transfer in fractured media is challenging. The presence of highly localized flow pattern and heat diffusion in the matrix has a significant effect on heat recovery or dissipation in both space and time. These processes influence the late time tailing of heat dissipation and recovery deviating from the classical conceptual model such as the equivalent porous media or the parallel plate model.

Many numerical and experimental investigations have been carried out to study heat transfer dynamics in fractured media.

[1] studied the effect of flow channeling on heat transfer in fractured rocks and they showed how the heat recovery in geothermal tests may be controlled by the fracture geometry.

[2] found a dynamic heat transfer coefficient between rock walls and the flowing fluid dependent on the fracture aperture.

[3] showed an experimental study of heat transport in fractured media. They concluded that at the laboratory scale the heat transport in fracture network has a dual porosity behaviour and the thermal dispersion played an important role on heat transfer dynamics.

On the basis of the laboratory experiment on heat transport in fractured media, [4] affirmed that it is not efficient to store thermal energy in rocks with high fracture density because the fracture are surrounded by a matrix with a more limited capability to store heat.

The present study is aimed at setting up a physical model to study heat transport dynamics in fractured media with parallel fractures varying the roughness, the aperture distribution and the fracture spacing. For this purpose the heat transport in a thermally isolated fractured block having a synthetic single fracture with known geometry has been investigated.

The observed behaviour has been compared with the one dimensional analytical solution for semi-infinite equally spaced parallel fractures embedded in a porous matrix [5]. The analytical model represented adequately the observed data and heat transport parameters. The effect of flow channeling and the fracture – matrix interaction is evident giving rise to an asymmetric distribution of the probability of residence time with a pronounced long tailing effect.

2. Theoretical background

Heat transport in discrete parallel fractures is subject to convective, diffusive and dispersive processes. Dispersion is caused by small-scale fracture aperture variation which causes flow channeling phenomena. The presence of the preferential flow paths has an important role on heat transport dynamics. The heat tends to migrate through the portion of fracture with the largest aperture.

Assuming that: 1) the width of each fracture is much smaller than its length; 2) there is a complete mixing process across the width of the fracture; 3) the permeability of the porous matrix is much lower and the heat transport within the matrix depends only on heat diffusion; 4) the heat transport along each fracture is much faster than transport within the matrix, the one dimensional advective-dispersive transport equation along a semi-infinite fracture with one dimensional diffusion in the rock matrix in perpendicular direction to the axis of each fracture is:

$$\frac{\partial T_f}{\partial t}+u_f\frac{\partial T_f}{\partial x}=\frac{\partial}{\partial x}\left(D_f\frac{\partial T_f}{\partial x}\right)-\frac{k_e}{\rho_w c_w \delta}\left.\frac{\partial T_m}{\partial z}\right|_{z=b} \qquad 0\le x\le\infty \tag{1}$$

Whereas the governing equation describing the heat diffusion in direction perpendicular to the fracture is:

$$\rho_m c_m\frac{\partial T_m}{\partial t}=k_e\frac{\partial^2 T_m}{\partial z^2} \qquad b\le z\le B \tag{2}$$

[5] presented an analytical solution for solute transport in semi-infinite equally spaced parallel fractures embedded in a porous matrix with a constant concentration at the fractures inlet (z = 0) and with initial concentration equal to zero. Since the governing equation of heat and solute transport highlights similarities between the two processes, the analytical solution of [5] can also be used for heat transport. In terms of heat transport, the analytical solution in Laplace space assumes the following expression:

$$T_f^*=\frac{T_0}{s}\exp(\nu L)\exp\left\{-\nu L\left[1+k^2\left(\frac{s^{1/2}}{A}\tanh\left(\sigma s^{1/2}\right)+s\right)\right]^{1/2}\right\} \tag{3}$$

The coefficient ν, A, k^2 and σ assume the following expression:

$$\nu=\frac{u_f}{2D_f} \tag{4}$$

$$A=\frac{\delta}{\sqrt{\theta D_e}} \tag{5}$$

Where $\theta=\rho_m c_m/\rho_w c_w$ and $D_e=k_e/\rho_w c_w$

$$\sigma=\frac{(B-b)}{D_e^{1/2}} \tag{6}$$

$$k^2 = \frac{4D_f}{u_f^2} \tag{7}$$

On the basis of this analytical solution the probability density function (PDF) of heat residence time in each fracture in the Laplace space can be expressed as:

$$PDF = \exp(\nu L)\exp\left\{-\nu L\left[1+k^2\left(\frac{s^{1/2}}{A}\tanh\left(\sigma s^{1/2}\right)+s\right)\right]^{1/2}\right\} \tag{8}$$

Given a generic temperature injection function $T_{inj}(0,t)$, the temperature function at the outlet of the each fracture is given by the convolution product between the inverse Laplace transform of the *PDF* and $T_{inj}(0,t)$ function.

3. Material and methods

The set-up of the physical model starts with the reconstruction of a fractured porous block having a single horizontal fracture with known geometry. The Synfrac [6] program has been used to generate a digitalized synthetic single fracture with a physical size of 204.8x204.8 mm^2 and a discretization of 1.6 mm. Figure 1 shows the geometry and fracture characteristics of the synthetic fracture.

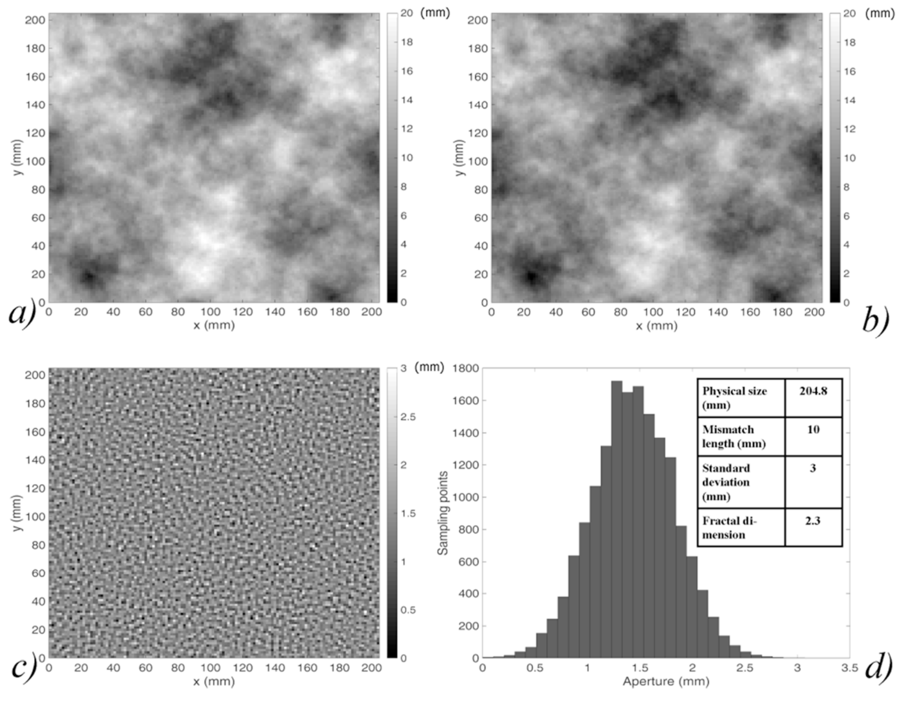

Fig. 1. Geometrical characteristics of the fracture generated by Synfrac (a) Top fracture surface; (b) bottom fracture surface; (c) fracture aperture; (d) aperture distribution and fracture characteristics.

A 3D printer AW3D AXIOM has been used to build the fracture planes using the ABS filament. Subsequently the fracture planes have been used as a mold in order to obtain the concrete fractured porous block with a thickness of 140 mm. The fractured porous block has been thermally insulated using an extruded polystyrene sheet (XPS) with a thickness of 20 mm and a thermal conductivity of 0.035 W/mK.

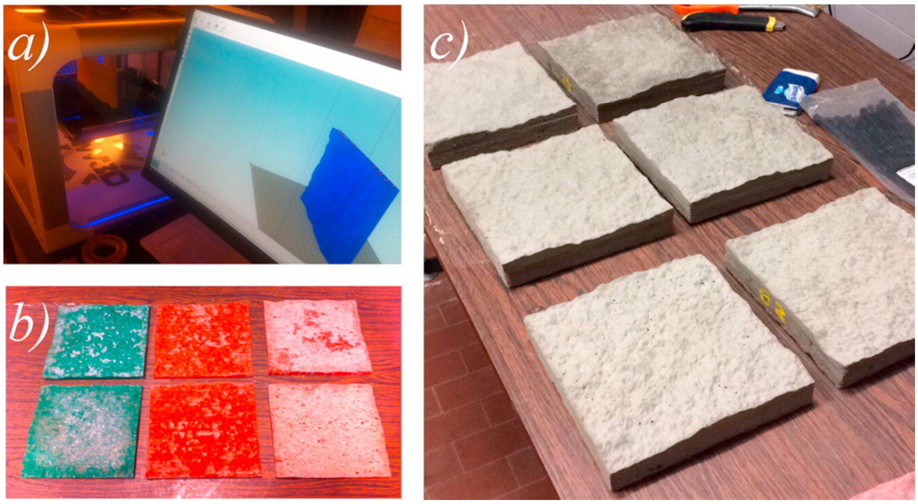

Fig. 2. (a) Fracture plane sheet built by 3d printer; (b) fracture plane sheet used as mold; (c) concrete porous fractured block with a thickness of 140 mm.

Furthermore the XPS has been used also to build the upstream and downstream flow cells with a spillway at different heights in order to maintain a constant head difference Δh.

Three thermocouples have been positioned uniformly in the upstream and downstream fracture width and they have been connected to a TC-08 thermocouple data logger (pico technology) and a sampling ratio of 1 second has been used.

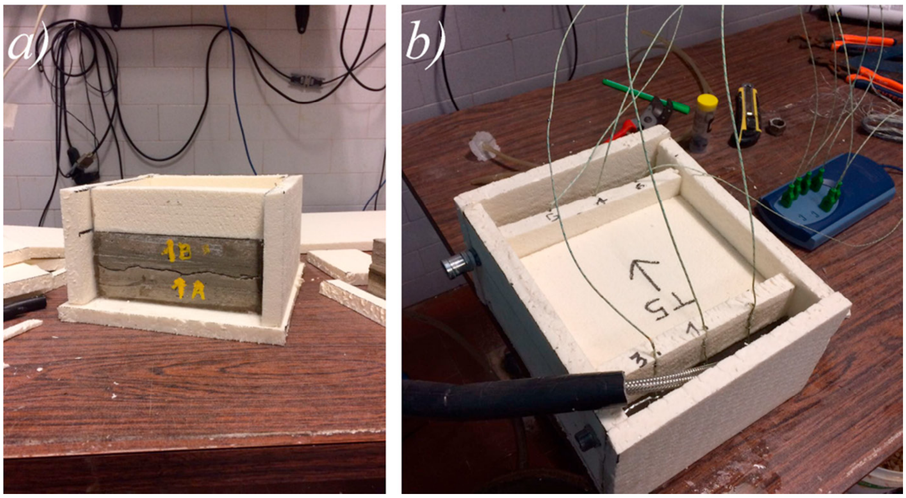

Fig. 3. (a) thermal insulation of fracture block using XPS; (b) thermally insulated fractured block with upstream and downstream flow cell and thermocouples.

Water flows through the fracture from upstream to downstream flow cells according to the imposed Δh. The water entering the upstream flow cell is heated by an electric water boiler with a volume of 10 liters.

The flow rate in the fracture is measured using the volumetric method, measuring the volume of water coming out from the downstream flow cell.

The heat transport test was performed by means of the following steps:

- At time t = 0 s the cold water valve has been opened and water flows reaching steady-state condition corresponding to the imposed Δh.
- At time t = 60 s, the cold water valve has been closed and at the same time the hot water valve has been opened.
- The time required for a volume of 0.25 liters to come out from the downstream flow cell is registered in order to estimate the flow rates.
- The thermal breakthrough curves (BTCs) for each thermocouple have been obtained.

The average function of the BTCs registered in the upstream flow cell has been used to represent the temperature injection boundary condition T_{inj}. Whereas the average function of the BTCs registered in downstream flow cell T_{obs} has been used for estimate the transport parameters using the one dimensional analytical solution for equally-spaced parallel fractures embedded in a porous medium. The theoretical BTC at the downstream cell (T_{sim}) has been obtained as the convolution product between T_{inj} and the unit response function representing the *PDF* obtained from the 1D analytical solution (equation 8) for the unitary pulse injection.

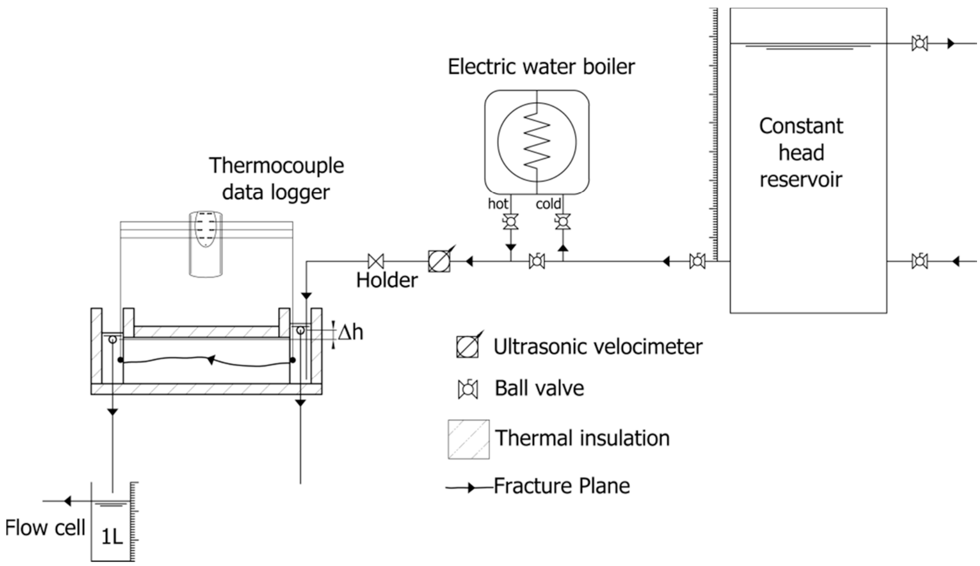

Fig. 4. Experimental setup.

4. Results

An average flow rate of $Q = 2.57\times10^{-6}$ m^3/s was measured by means of the volumetric method corresponding to a hydraulic gradient equal to $i = 0.0011$ m/m. Considering a fracture length of $L = 0.2048$ m the equivalent fracture transmissivity is equal to $TRA_{eq} = 1.17\times10^{-2}$ m^2/s.

In order to determine the heat transport parameters T_{obs} has been compared with T_{sim}. The root mean square error (RMSE) between T_{sim} and T_{obs} has been used as a criterion to evaluate the goodness of the fitting results. The figure 5 shows the fitting results.

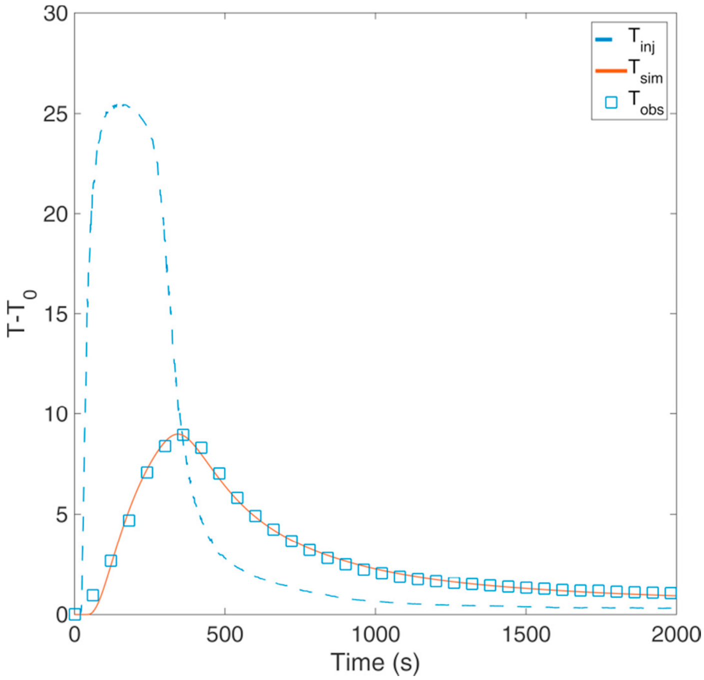

Fig. 5. Fitting results using the 1D analytical solution for equally spaced parallel fractures embedded in a porous medium.

In the table 1 are reported the estimated heat transport parameters.

Table 1. Heat transport parameters estimated using the 1D analytical solution for equally spaced parallel fractures embedded in a porous matrix.

Reynolds number	Re	25.66 m/s
Convective velocity	v	0.0045 m/s
Thermal dispersion	D	0.00625 m^2/s
Effective thermal diffusion	D_e	1.1186×10^{-10} m^2/s
Boundary layer thickness	δ	2.4986×10^{-4}

The figure 6 shows the estimated probability density function of the residence time. The effect of the heat exchange between the fracture and porous matrix is evident, as the curve shows an asymmetric distribution, characterized by long tailing.

In fact the descending limb of the *PDF* of the residence time has a variable slope instead of a constant one which would be the case in thermal equilibrium conditions.

The transport of heat in fractured reservoirs is strongly affected by the fracture-matrix interfacial area which controls the effective heat transfer area between the fracture network and the matrix rock [7] by diffusion, a significant mechanisms for fracture-matrix exchange.

Since heat diffusivity is much larger than solute diffusivity, heat transfer processes may be more sensitive to fracture-matrix diffusion processes than advective dispersion processes.

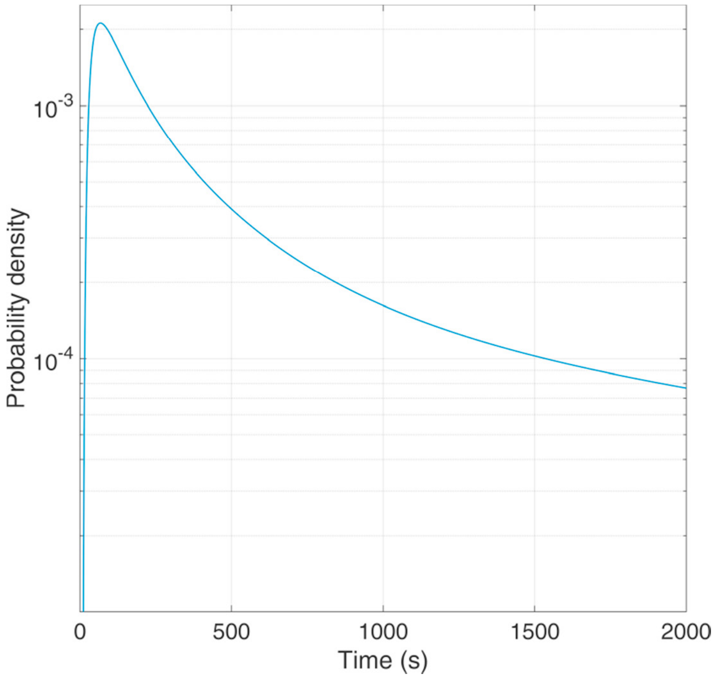

Fig. 6. Probability density function of the residence time evaluated using the 1D analytical solution for equally spaced parallel fractures embedded in a porous matrix.

The obtained results encourage to continue the experiments varying the aperture distribution, roughness and the fracture-matrix size ratio in order to evaluate the key parameters affecting heat transport in fractured media.

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