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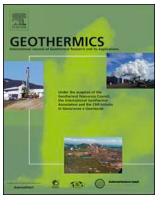

Synthetic investigation of thermal storage capacities in crystalline bedrock through a regular fracture network as heat exchanger

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ABSTRACT

Crystalline rocks are in general considered of poor interest for geothermal applications at shallow depths (< 100 m), in particular because of their low permeability. In some cases, fractures may enhance permeability, but thermal energy storage at these shallow depths still remains challenging because of the complexity of fractured media to efficiently manage water circulation. To assess the feasibility of efficient thermal energy storage in shallow fractured crystalline bedrocks and to determine the fracture network geometric parameters that control heat storage in fractured media, we investigate abilities of a synthetic model especially dedicated to an innovative semi open-loop heat exchanger. The representative heat exchanger system consists of a network of star-shaped grooves radially arranged around a central borehole hydraulically and thermally insulated from the grooves. Fluid is injected in the downward direction into the grooves and withdrawn upward in the central insulated pipe. Heat is exchanged with the rock only through the grooves. The three geometrical parameters controlling the thermal storage are the width, the height and the number of grooves. With a dimensional analysis on heat transport equations and a sensitivity analysis on geometric parameters, we show that the conduction of temperature in rocks presents two well-separated short-term and long-term regimes. At short-term, maximum of exchanges is reached at the beginning of the heated water injection into the grooves. It is controlled by the thermal exchange surface depending on the number and width of the grooves. During the long-term regime, the heat exchanger capacity is mainly controlled by the accessible rock to thermal storage which depends mainly on the width of the grooves. We finally discuss about the possibility of extending the results obtained from the star-shaped geometric sensitivity study to natural fracture systems.

1. Introduction

As a result of the necessity to reduce greenhouse gases, ground source heat pump systems increase in popularity. Thermal energy storage is currently developed in shallow productive aquifers to store energy produced by solar panels or for achieving periodic heating and cooling. Thermal storage is classically achieved with geothermal probe, a closed-loop heat exchanger composed of a vertical U-tube where a heat transfer fluid circulates (Stauffer et al., 2013) or with ATES - Aquifer Thermal Energy Storage which consists in horizontal circulation of a heat transfer fluid between two boreholes (open-loop well-doublet) (Banks, 2009; Molz et al., 1983; Sauty et al., 1982). Recently SCW - stand / standing column well, a semi-closed loop geothermal heat exchanger, was proposed for thermal energy storage at shallow depth (< 200 m). It is made of a unique coaxial borehole allowing vertical circulation of a heat transfer fluid in an open-loop circuit (Deng et al., 2005; Lee, 2011; Nguyen et al., 2015; Pasquier et al., 2016; Rode et al., 2015; Woods and Ortega, 2011). The main advantage of SCW compared to geothermal doublets, is that it can be installed in dense urban area due to its vertical configuration (Pasquier et al., 2016). The external annulus of the borehole allows direct contact between fluid and rocks which should improve thermal exchanges compared to geothermal probe where heat transfer occurs only by conduction. In sedimentary rocks, the fluid circulating in the SCW can easily penetrate in the porous media and heat is stored in the rock materials and in water filling the pores (Rode et al., 2015; Deng et al., 2005; Lee, 2011). In low-permeability rocks, like crystalline rocks, heat storage in the SCW occurs only in the surrounding rock matrix, by radial thermal conduction (Pasquier et al., 2016; Nguyen et al., 2015, Woods and Ortega, 2011). In this study we discuss about the thermal behavior of a SCW made of fractures, implemented in crystalline rocks.

In crystalline rocks, a way to increase heat exchanges between the

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Nomenclature

b	groove aperture (m)
D_m	thermal diffusivity in the rock matrix (m^2/s)
D_g	thermal diffusivity in the grooves (m^2/s)
E	thermal stored energy in the rock matrix x (J)
H	height of the grooves (m)
l	width of the grooves (m)
n	number of grooves
Pe_g	Péclet number between advection in the groove and conduction in the groove
Pe_m	Péclet number between advection in the groove and conduction in the rock matrix
P	thermal power of exchange between the fluid and the rock matrix (W)
P_{max}	maximal thermal power of exchange between the fluid and the rock matrix (W)
Q	total flow rate (m^3/s)
r	radial distance (m)
r_w	borehole radius (m)
S	surface of exchange between the fluid and the rock matrix (m^2)
t	time (s)
t_{c1}	time for thermal front to cross the minimal half distance between two grooves: start of transition regime (s)
t_{c2}	time for thermal front to cross the maximal half distance between two grooves: end of transition regime (s)
t_c	mean transition time (s)
T_g	temperature in the grooves (K)
T_m	temperature in the rock matrix (K)
T_0	initial temperature (K)
T_i	injection temperature in the grooves (K)
T_{tf}	temperature of the thermal front in the rock matrix (K)
u	mean fluid velocity in the grooves (m/s)
V_g	total volume of the grooves (m^3)
V_r	volume of the rock matrix between the fractures where heat advection occurs (m^3)
V_f	volume of the fractures where heat advection occurs (m^3)
x	x Cartesian coordinate (m)
y	y Cartesian coordinate (m)
x_m	minimal half distance between two grooves (m)
X_m	maximal half distance between two grooves (m)
z	z Cartesian coordinate (m)
θ	angular coordinate
Ω_g	groove domain in Cartesian coordinates
Ω_m	rock matrix domain in cylindrical coordinates
	for indicating dimensionless variables

fluid and the matrix in a SCW, would be to manage the fluid directly in existing fractures, which is still a challenge. Indeed, if fractures may increase permeability and injection capacities, it may be difficult to recover the fluid injected in such complex media, in particular due to the spatial variability of hydraulic properties and to the relatively low permeability of crystalline rock (Axelsson et al., 2001; Berkowitz, 2002; Neuman, 2005). Hydraulic fracturing or stimulation is usually used to develop the fracture system and increase the permeability of Enhanced Geothermal Systems (EGS) (Haring et al., 2008; Zimmermann and Reinicke, 2010). Such a process appears to be inappropriate to promote homogeneous vertical circulation all around a borehole, because fractures tend to propagate to a large distance perpendicularly from the borehole axis (Hossain et al., 2000; Lee and Haimson, 1989) and not in a vertical arrangement. The vertical development of fluid circulation in the media could be theoretically achieved by the creation of grooves along the borehole wall with different known drilling techniques. For instance, lowering along the borehole a jet system which splatters sand at high pressure on the wall of the borehole should allow to make grooves of few tens of centimeters (Cobbett, 1999). Such developments in low-permeability media should allow circulation of fluids for geothermal storage. Thus, if it seems possible to improve permeability in crystalline rocks, it is necessary to ensure that the developed artificial fracture network is optimal for geothermal applications.

In this perspective, we model heat transport in a simple predetermined fracture system to test heat storage capacity of such fractured medium and to determine the parameters that control heat exchange between fractures and the surrounding rocks (the matrix). Transport and exchanges of heat in fractured media are mainly controlled by the cumulative surface area of the fractures, by the cumulative volume of the fractures, and by the volume of rock effectively accessible during a thermal storage process. The above cumulative surface area and volume are controlled by the number and lengths of fractures where thermal advection occurs. The volume of the fractures influences the transit time of flow in the fracture system and is described by the mean aperture of the fractures. The role of each parameter on thermal exchange and on heat storage capacity is not obvious due to the structural complexity of the media and to the fact that they are all linked. For instance, increasing the number of fractures allows to improve the exchange of heat between the fluid and the rock but impacts the volume of rock between fractures which constitutes the solid part of the heat storage capacity; a corollary question then concerns the contribution of fluids to the storage capacity. Thus, the challenge of this study is to discriminate the effect of geometrical and hydraulic parameters, on thermal transport.

The effect of the geometry of simple fracture systems on heat transfer in crystalline media has already been analyzed thanks to the modelling of thermal transport at fracture scale and fracture network scale. At fracture scale, it is mainly the effect of fracture aperture and roughness on thermal exchanges between the fracture and the matrix that has been highlighted (Guo et al., 2016; Klepikova et al., 2016; Neuville et al., 2010). For deep geothermal applications, Guo et al. (2016) show that the performance of an EGS system is controlled by the aperture distribution of fractures. At the network scale, the effect of hydrodynamic and thermal parameters of complex fracture structures has been tested on heat transport and exchange (Geiger and Emmanuel, 2010; Kolditz, 1995; Kolditz and Clauser, 1998; Molson et al., 2007). For instance, Geiger and Emmanuel (2010) characterize in 2D the impact of matrix permeability on the spatial distribution of the temperature field. Nevertheless, these studies did not provide any simple relationship between the geometry of the fracture network and the heat exchange capacities.

Heat transport has been also studied in more deterministic fracture networks made up of several equally spaced horizontal fractures, for characterizing heat extraction capacity in a geothermal reservoir (Bodvarsson and Tsang, 1982; Gringarten et al., 1975; Wu et al., 2016). With a semi-analytical modelling of heat extraction through parallel fractures in a geothermal reservoir, Wu et al. (2016) propose optimal values of the number of fractures and fracture spacing to maximize the EGS lifetime. Applying a similar approach, we assess the effect of fracture geometry and matrix block size on the performance of geothermal storage at shallow depth. For this, we simulate numerically the behavior of a semi-open geothermal heat exchanger (specific standing column well), implemented in the context of a simple network of predetermined fractures. Because such a heat exchanger can work at different frequencies of heat storage/production, depending on thermal resources and uses, we aim at characterizing the parameters that control the thermal capacity of this kind of heat exchanger. The simulation of the behavior of the whole system is based on a reduced set of