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Influence of groundwater flow in fractured aquifers on standing column wells performance

A. Nguyen*, P. Pasquier, D. Marcotte

Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, P.O. Box 6079, Station Centre-Ville, Montréal, Canada H3C 3A7

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ABSTRACT

A coupled model of a standing column well is developed to evaluate the influence of groundwater flow in fractured aquifers. Heat transfer and groundwater flow within a standing column well and its surrounding ground is modeled by means of a resistance and capacity network. The work demonstrates that the presence of a single fracture zone embedded within the bedrock has a significant beneficial effect on the performance of standing column wells. Temperature differences between the homogeneous and fractured aquifer were particularly important when the well was operated at typical bleed ratios. The results show that the model developed in this paper is in good agreement with numerical reference solutions.

1. Introduction

A standing column well (SCW) is a type of ground heat exchanger (GHE) forming part of a ground-source heat pump (GSHP) system and consists of a deep vertical borehole filled with groundwater up to the water table level. In a SCW, groundwater is usually pumped from the base of the well through a dip tube and transferred to the building's heat pump before being reintroduced at the top of the well, in the annular region (Fig. 1).

During peak operation periods, the system can discharge part of the pumped groundwater away and induce a groundwater flow into the SCW, a feature commonly known as *bleed*. The configuration of SCWs coupled with the ability to renew their water content are such that, in comparison to a conventional vertical closed-loop GHE, they allow significant reduction in total required drilling length for a given thermal load, which generally leads to a reduction of the construction costs of GSHP systems (Deng O'Neill et al., 2006).

SCW systems are, however, more complex than conventional closed-loop GHEs since the underground heat transfer includes advection in addition to conduction. Various numerical models were developed to assess their thermal response under a given load (Deng, 2004; Rees et al., 2004; Abu-Nada et al., 2008; Ng et al., 2011; Croteau, 2011; Nguyen et al., 2012). In order to simplify the problem, most contributions assumed that the surrounding aquifer is homogeneous and isotropic. When bleed is activated under this assumption, the induced groundwater flow is slightly increasing linearly with the depth of the well.

In practice, given the significant depth of SCWs (i.e. 300–500 m), it is common when drilling in bedrock to intercept fracture zones that lead to a local increase of water inflow. One might suspect that these local fracture zones are likely to affect the thermal response of the water circulating within the SCW after any activation of the bleed.

Only a handful of studies have been conducted to assess the way the hydraulic component is taken into account in SCW models. The first work related to this topic was carried out by Deng (2004), who demonstrated that the aquifer hydraulic conductivity had a marginal effect on the performance of SCWs. However, this is true only when the aquifer is considered homogeneous and, in such cases, the hydraulic conductivity influences only the hydraulic drawdown.

Deng et al. (2005) also developed a simplified one-dimensional finite difference model to assess the influence of fracture flow on the system's performance using a *by-pass* approximation where groundwater bypasses the surrounding ground and comes straight into the borehole at the undisturbed temperature. According to Deng's results, the performance of the SCW system is better when groundwater flows only in a homogeneous porous medium than when a similar flow occurs in a fracture embedded in an imper-

* Corresponding author.
E-mail address: t.nguyen@polymtl.ca (A. Nguyen).

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Nomenclature

A	area (m^2)
b	aquifer thickness (m)
C	thermal capacity (J/K)
c	volumetric heat capacity (J/(m^3 K))
COP	coefficient of performance (–)
CAP	capacity (W/unit)
EWT	entering water temperature (K)
H	hydraulic head (m)
K	hydraulic conductivity (m/s)
k	thermal conductivity (W/(m K))
LWT	leaving water temperature (K)
l	fracture zone thickness (m)
n	number of active heat pumps (–) or number of nodes (–)
n	number nodes (–)
r	radius (m)
R_T	radial thermal resistance (K/W)
$\tilde{R}_T$	vertical thermal resistance (K/W)
R_H	radial hydraulic resistance (s/m^2)
$\tilde{R}_H$	vertical hydraulic resistance (s/m^2)
S	storage (m^2)
s	specific storage (m^{-1})
t	time (s)
T	temperature (°C)
$\dot{V}$	pumping flow rate (m^3/s)
v	control volume (m^3)
z	depth (m)

Greek symbols

β	bleed ratio (%)
ϕ	hydraulic contrast ratio (–)
ρ	density (kg/m^3)
ν	velocity (m/s)

Subscripts

fi	inner fluid
p	pipe
fo	outer fluid
A	aquifer
aa	advection in aquifer
da	diffusion in aquifer
D	Darcy
i	time step index
j	node index
K	neighboring node index

Acronyms

GHE	ground heat exchanger
SCW	standing column well
TRCM	thermal resistance and capacity model

meable medium. The author mentions that this is presumably because in the medium, the groundwater flow, which enhances heat transfer, is spread over the surrounding ground volume. This conclusion is quite counter-intuitive since groundwater inflow at undisturbed temperature should be beneficial for the SCW system. As pointed out by Deng (2004), further investigations that combine heat and mass transfer in the fractures surrounding the SCW are suggested.

To evaluate the influence of a single fracture on the bleed, Ramesh and Spitler (2012) developed a quasi-2D finite difference model and implemented heat advection along certain layers of the model. According to their results, the performance was significantly degraded in such cases. The authors however did not model groundwater flow, an important aspect in the vertical distribution of hydraulic fluxes. Therefore, these results cannot be extrapolated to predict the effect of bleed in fractured aquifers.

Modeling heat exchange between groundwater and fractured aquifers is a complex problem and hence remains a major challenge. Indeed, estimating heat dissipation in fractured rock needs a clear understanding of the flow regime along the fractures. In fact, the modeling of flow in fractured geological media is in self a highly complex problem and can require an exhaustive geometrical characterization of fractures and fracture networks. Available modeling approaches, all of which can be formulated in deterministic and stochastic frameworks, are traditionally divided into two rough classes: discrete fracture models and continuum models and are reviewed by Berkowitz (2002). The merit of these approaches is not discussed here, both having their advantages and limitations. Note however that the choice of the method often remains a subject of debate due to the natural uncertainty associated with identification of fracture properties.

Nevertheless, research has shown that flow in fractured medium in some cases can be reasonably represented by flow through an equivalent porous medium (Singhal and Gupta, 2010). This would be true when (a) fracture density is high, (b) apertures are constant rather than varying, (c) orientations are distributed rather than constant and (d) the interest is mainly on volumetric flow. Under these conditions, the fracture zone can be simplified to a homogeneous porous layer by using a continuum approach.

On that note, Croteau (2011) used a fully coupled finite element model for SCW systems integrating a porous layer representing a fracture zone and obtained results in contradiction with the results of Deng (2004) and Ramesh and Spitler (2012). For a constant heat injection of 70 kW over 72 h, Croteau (2011) noticed that the presence of a single fracture zone within the bedrock has a significant beneficial effect on the performance of SCWs when bleed was activated. Temperature differences between the porous medium model and the fractured model of equivalent hydraulic conductivity of 3.2 and 0.84 °C were observed when the SCW was operated at bleed ratios of 10–20% respectively, which corresponds to typical bleed percentages. For bleed ratios greater or equal to 30%, the temperatures of the two models were virtually identical.

Nguyen et al. (2013, 2015) presented a fully coupled multiphysics model involving heat transfer and groundwater flow for SCW systems using a thermal resistance and capacity network, a method adopted by several authors (Zarrella et al., 2011; Bauer et al., 2011; Pasquier and Marcotte, 2012), in conjunction with the Theis solution, which was validated against a reference finite element model. They showed that use of bleed control can enhance considerably the overall heat transfer efficiency with the surrounding ground. Although the original model is restricted to homogeneous aquifers, the concept of resistances and capacities can also be applied to represent the hydraulic components of the SCW, allowing the integration of a fracture zone.

The works presented hereinafter are a direct extension of previous works and aim to present a model taking into account three layers with different hydraulic properties to represent a fracture zone. The objectives of this paper are threefold: (1) present a coupled model designed to account for a fracture zone represented by an equivalent porous medium layer, (2) present a validation of the model against a reference solution and, (3) assess the influence of a fractured zone on SCW systems when bleed is used.

2. Methodology

In the following sections, a brief overview of the SCW model will be presented to allow the reader to understand the contribution