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Thermal resistance and capacity model for standing column wells operating under a bleed control

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ABSTRACT

A fully coupled multiphysics model involving heat transfer and groundwater flow within a standing column well and its surrounding ground was modeled by means of a thermal resistance and capacity network coupled to an analytical solution. The transient groundwater velocity field and aquifer drawdown are addressed by applying a temporal superposition technique to the so-called Theis analytical equation. The heat pumps are integrated into the model, thereby allowing the effect of its entering water temperature on its capacity and coefficient of performance to be accounted for. To increase the flexibility of the approach, a three-level bleed control and an on-off sequence is included in the model, in order to allow the simulation of the dynamics of a system operation. The results show that the model developed in this paper is consistent with numerical reference solutions.

1. Introduction

In many countries, ground coupled heat pump systems (GCHPS) are considered to be an environmentally friendly technology with a wide range of applications such as space heating and air conditioning for commercial and institutional buildings. Among these systems, standing column well (SCW) systems, which consist in a deep vertical borehole filled with groundwater up to the water table level, have the potential to deliver much higher heat exchange rates than conventional GCHPS made of vertical closed-loop borehole heat exchangers (BHE) [26].

In a SCW, groundwater is first pumped from the base of a well to a plate heat exchanger to prevent fouling in the heat pump before being re-injected at the top of the same well (Fig. 1). To help maintain the heat pump's entering water temperature (EWT) within its operational limits during peak periods, the performance of the system can be enhanced by discharging part of the pumped water, thereby creating a drawdown that induces groundwater flow to the SCW. This operation, known as bleed, is a key feature to enhance heat exchange with the surrounding ground as it includes advection as heat transport mechanism in addition to conduction.

Some regulatory agencies require to return the bleeding water to the same aquifer through an injection well. In such case, the injection well should be far enough so that no thermal short-circuiting occurs with the SCW. Otherwise, the bleed water can be diverted elsewhere. Multiple bleed levels can be implemented in order to reduce the volume of discharged groundwater and limit the aquifer drawdown, or simply to reduce the power consumption of the submersible pumps, which increases with the lowering of the groundwater level in the well.

In cold climates, the bleed control is sometimes not sufficient to stabilize the groundwater temperature inside the SCW. To prevent the mechanical failure of the heat pumps, an on-off sequence can be initiated, thereby gradually decreasing the thermal ground load (e.g. shutting down sequentially the building's heat pump compressors) until the EWT returns to a suitable temperature. During that time, an auxiliary heating system is required.

In recent years, a growing number of SCWs have been installed in regions where geological and hydrogeological conditions are suitable [10,19]. The increased popularity of such systems is due to the high thermal efficiency of SCWs, but also to the fact that SCWs require less land area than conventional closed-loop systems, an important factor in urban areas where there is little space between buildings.

Considering the complex underground thermal and hydraulic processes of SCW systems, various numerical models using finite volume and finite element methods were developed [1,6,8,14,24]. However, these numerical models are computationally too heavy to be used in hourly simulation programs or design tools. Therefore, they are often simplified in actual designs by rules of thumb or

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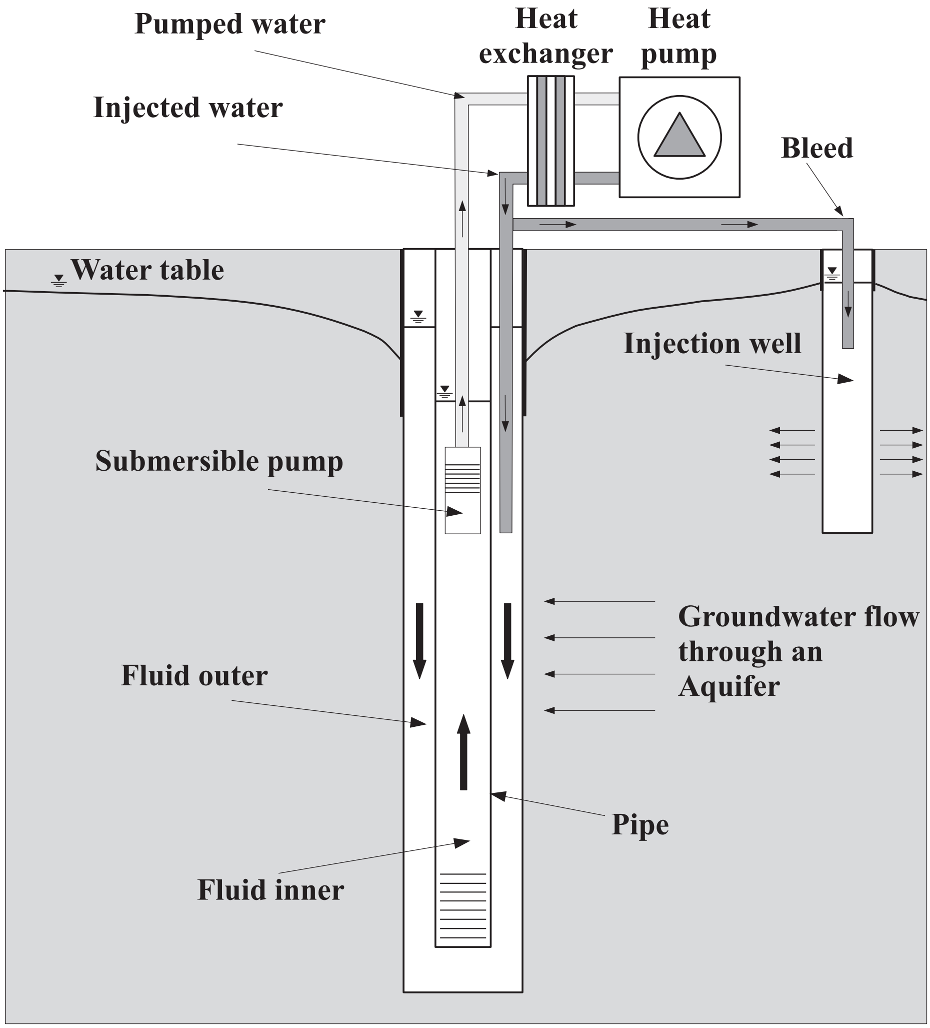

Fig. 1. Illustration of a SCW system.

approximations. This is why, recent research efforts have focused on the development of simplified models for SCW systems [9,16,23].

Ref. [9] used a 1D finite difference aquifer model, thus considering a uniform heat flux and temperature along the borehole wall. Furthermore, the borehole is modeled as a single node and the temperature of this node is approximated by the arithmetic mean value of the entering and leaving water temperatures. As a result [23], mentioned that the thermal short-circuit between the upward and downward fluid is not adequately accounted for.

In order to substantially reduce the computation cost of modeling the underground heat transfer problem without further simplifications, the system can be described as a network of thermal resistances and capacities, thereby transforming the advection-diffusion partial differential equation into a system of ordinary differential equation (ODE). Several authors have proposed this method to model the thermal energy transfer between the various component of a closed-loop borehole heat exchanger under the assumption of pure heat conduction [2,3,7,12,20,22,28].

Ref. [23] recently used a similar approach for a quasi two-dimensional SCW where the borehole is 2D and the surrounding ground is 1D. The authors attempted to adequately model the thermal short-circuit between the injected and pumped water inside the SCW and to improve Deng's simplified 1D model. In their model [23], neglected the transient hydraulic head variation in the aquifer by assuming that a drawdown cone around the well is instantly developed, which sometimes take a few days in aquifers.

This paper presents a dynamic 2D axisymmetric thermal resistance and capacity model (TRCM) that couples transient heat transfer and groundwater flow in a SCW system. The integration of the transient component of the groundwater flow allows to take into account the temporal evolution of the groundwater velocity field and the well drawdown during bleed operations, an original contribution to the field. To increase the flexibility of the proposed approach, a three-level bleed control as well as a heat-pump on-off sequence is also incorporated into the model. This work is an extended presentation of the work done by Ref. [16] as it introduces additional features and presents original validation scenarios.

2. Methodology

In the following section, the approach used to construct the model is presented with sufficient details to allow the interested reader to reproduce the results presented hereinafter. To simplify the complex heat and mass transfer process involved in a SCW, the real geometry described in Fig. 1 was simplified to the geometry presented in Fig. 2 and all developments presented in this section are based on the following assumptions: