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A moving finite line source model to simulate borehole heat exchangers with groundwater advection

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ABSTRACT

Available analytical models for the thermal analysis of ground source heat pumps (GSHPs) either neglect groundwater flow or axial effects. In the present study a new analytical approach which considers both effects is developed. Comparison with existing analytical solutions based on the finite and infinite line source theory is carried out. This study shows that in general the heat transfer at the borehole heat exchanger (BHE) is affected by groundwater flow and axial effects. The latter is even more important for long simulation times and short borehole lengths. At the borehole wall the influence of the axial effect is restricted to Peclet numbers lower than 10, assuming the BHE length as characteristic length. Moreover, the influence of groundwater flow is negligible for Peclet numbers lower than 1.2. As a result for Peclet numbers between 1.2 and 10 the combined effect of groundwater flow and axial effects has to be accounted for when evaluating the temperature response of a BHE at the borehole wall and thus the use of the moving finite line source model is required.

1. Introduction

Ground source heat pump (GSHP) systems are one of the major technologies for shallow geothermal energy production in many countries [1,2]. Through their use, significant amounts of fossil fuels can be saved and thus additional CO_2 emissions can be avoided [3,4]. GSHP systems are closed systems, in which a heat carrier fluid is circulated within a buried vertical or horizontal borehole heat exchanger (BHE). By slow and permanent circulation, exchange of heat with the surrounding underground is accomplished, which is utilized for space heating, air conditioning and hot water supply of both commercial and residential buildings. Vertical borehole configurations are often favored to horizontal collectors because of their smaller space requirements and because they are less influenced by seasonal temperature fluctuations from the surface. In this system, one or more vertical pipes are installed down to depths of around 50–150 m [5], depending on the prevailing geological conditions and the specific energy demand.

In order to estimate the heat transfer at the vertical BHE, different numerical [6–11] and analytical methods [12–21] as well as combination of the latter have been proposed [15,22,23]. Analytical solutions are widely used because of their simplicity and speed in computation. Most of the analytical approaches for the thermal analysis of BHEs presume conduction-dominated systems (i.e. natural groundwater flow is not considered), and they are based on the infinite line source or cylindrical source theory [13,15]. They are in particular applied for the evaluation of short-term geothermal field experiments such as thermal response tests (TRT) which usually range from 12 to 60 h [24]. These models, however, are less adequate for long-term simulations when axial effects become relevant, usually after 1.6 year of operation depending on the hydrogeological and operational conditions [25]. The temperature response for an infinite line source model (without groundwater flow) cannot reach steady state conditions and the temperature anomaly will increase to infinity with operation time.

In contrast, the temperature response converges to steady state conditions when accounting for a finite length of the borehole and hence axial effects are considered. Axial effects can be quantified as the differences between the results obtained by using finite and infinite line source methods. The axial heat conduction at the bottom of the borehole accelerates the heat exchange between heat carrier fluid and the surrounding underground, and thus has to be regarded for optimal borehole design. For a specific energy demand

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