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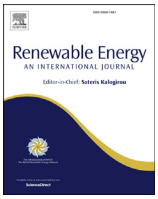

Thermal evaluation of coaxial deep borehole heat exchangers

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ABSTRACT

This paper presents a performance study of deep borehole heat exchangers. The coaxial borehole heat exchanger (BHE) has been selected because for the present conditions it has a better performance than the conventional U-tube BHE. A numerical model has been developed to study the coaxial BHE. The model predictions are compared to detailed distributed temperature measurements obtained during a thermal response test. The model is found to accurately predict the behavior of a coaxial BHE. The influence of the flow direction of the mass flow is studied for BHEs in the range 200 m–500 m. A parametric performance study is then carried out for the coaxial case with different borehole depths, flow rates and collector properties. The results clearly show a significant increase in the system performance with depth. In addition, it is shown that with increasing borehole depth, the heat load that can be sustained by the BHE is significantly increased. An overall performance chart for coaxial BHEs for the depths of 300–1000 m is presented. The chart can be used as a guide when sizing deep BHE installations.

1. Introduction

Ground source heat pump systems usually utilize borehole heat exchangers (BHEs) 100–300 m deep as a source and sink for thermal energy. For smaller systems, this type of installations can be made space effective and have a small or negligible visual footprint. Still, larger systems require a certain amount of space (drilling area) which might be hard to find in densely populated urban areas, such as city centers.

As discussed in Ref. [11,12]; there are two ways of upscaling BHE installations, either by increasing the number of boreholes or by increasing the depths of the boreholes. Although, the first alternative stands for the majority of the installations today, installations with BHEs based on 400–500 m boreholes are now being constructed on a commercial basis in Norway and Sweden. The deeper boreholes, which are more expensive than the conventional boreholes, are in these cases motivated by scarcity of space.

In Scandinavia, the temperature in the undisturbed ground increases with about 1.0–3 K/100 m, thus the thermal potential for heat extraction increases with increasing depth while the potential for cooling purposes decreases. Therefore, the prospects of using BHE based on deep boreholes are most feasible (but not limited too) for buildings with large heating loads and either small or negligible cooling loads.

With increasing depth, the flow rate of the heat carrier has to be increased for the BHE to be effective (i.e. decrease the thermal contact between down and up-going fluid, thermal shunt). Therefore, also the flow area of the collector has to be increased in order to avoid excessively high pressure drops. In comparison with the conventional U-tube collector, the coaxial BHE utilizes a larger fraction of the borehole cross sectional area as flow area. It is, therefore, more appropriate for deeper boreholes since a larger mass flow rate can be used.

The coaxial BHE has also been shown to have a better thermal performance than the conventional U-tube collector [2]. In addition, changes in the physical dimensions and properties of the center pipe can be applied to reduce the thermal shunt between down and up-going fluid. The present paper focuses on the coaxial BHE and its performance in boreholes in the depth range 200 m–1000 m.

The boreholes are cost intensive, and it is, therefore, important to have a sound knowledge of the heat extraction rates that can be expected. The thermal performance of the coaxial BHE can be determined using either analytical or numerical simulation models. The analytical models can be made computationally cost effective,

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Nomenclature

Symbol

C	Specific heat capacity [J/kg·K]
D_h	Hydraulic diameter [m]
f	Friction factor [−]
h	Heat transfer coefficient [W/m^2·K]
k	Thermal conductivity [W/m·K]
$\dot{m}$	Mass flow [kg/s]
ΔP	Pressure drop [Pa]
Q	Heat load [W]
Tf_{mean}	Mean fluid temperature, $(T_{inlet} + T_{outlet})/2$ [K]
q'	Specific heat load [W/m]
q''	Heat flux [W/m^2]
r_1	Collector inner radius [m]
r_2	Collector outer radius [m]
r	Radius [m]
r^*	Radius ratio [−]
R	Thermal resistance [K·m/W]
S	Source term [W/m]
s	Wall thickness [mm]
T	Temperature [K]
t	Time [s]
u	Internal energy [J/kg]
V	Velocity [m/s]
L	Borehole depth [m]
W	Electric effect [W]
GG	Geothermal gradient [K/km]

Greek letters

α	Thermal diffusivity, $k/\rho C$ [m^2/s]
Δ	Finite increment in a variable
ρ	Density [kg/m^3]
ν	Kinematic viscosity [m^2/s]
η	Pump Efficiency [%]

Dimensionless numbers

Pr	Prandtl number, ν/α [−]
Nu	Nusselt number, hL/k [−]
COP	Coefficient of performance, $\frac{Q+W_{hp}}{W_{hp}}$ [−]
COP_{total}	Total COP, $\frac{Q+W_{hp}}{W_{hp}+W_p}$ [−]

Index

a	Annular
c	Center pipe
g	Ground
w	Water
f	Heat carrier fluid
o	Outer
b	Borehole
n	Index, temporal discretization
i	Index, spatial discretization (radial)
j	Index, spatial discretization (vertical)
p	Pump
hp	Heat pump
inlet	BHE inlet properties
outlet	BHE outlet properties

but they are in general not capable of describing all the involved phenomena, and therefore, lack some of the accuracy, flexibility and transparency gained from numerical methods.

Efficient numerical models can be implemented by applying the analogy to electric networks when describing the thermal resistances within the borehole; thus representing a geometrical simplification where the different parts of the borehole are described by single nodes. A numerical grid is then used to describe the bedrock around the borehole in two or three dimensions, while the borehole, the collector and the heat carrier are simulated as one-dimensional features. Numerical models based on this methodology have earlier been referred to as thermal resistance and capacity models (TRCM), [3]. TRCM models for coaxial BHEs have been published by Refs. [3–6,10].

Although, comparisons were made with experimental measurements of outlet and inlet fluid temperatures in Refs. [3,4] and in Ref. [10]; neither of these models were compared with detailed experimental data from distributed temperature measurements during operation of the BHE.

In the present paper, the coaxial BHE is analyzed using a new numerical model. The model is validated through comparison with detailed distributed temperature measurements performed by Ref. [2].

The model is then used to study the performance of coaxial BHEs as a function of the total borehole depth, the mass flow rates and the collector properties.

It is shown that with increasing borehole depth, the heat load that can be sustained by the BHE is significantly increased as compared with conventional 200–300 m BHEs. With increasing borehole depth, the required circulation pump effect increases; it is, however, clearly shown, that the increase is manageable and small comparative with the gain in thermal effect. In addition, it is possible to compensate for an increased pressure drop using a larger borehole diameter.

2. Objectives and methodology

2.1. Introduction

The objective of the paper is to analyze and establish the performance of coaxial BHEs for boreholes deeper than the conventional 200 m–300 m.

It is assumed that the BHE is constructed as a coaxial pipe-in-pipe BHE which uses water as the heat carrier. The water in the annular space is separated from the borehole wall by a thin membrane. This type of installation has been demonstrated by Ref. [2]; and it can be categorized as a closed or near closed system.

The benefits of having a closed, or a near closed system is that the water or heat carrier fluid is kept clean from contaminants that can deposit in, for example, the heat exchangers. Using water as the heat carrier also reflects the intention of using a slightly higher operation temperature, as compared to conventional BHE installations which often operate with fluid temperatures below 0 °C during peak load.

A new numerical model for the coaxial BHE is developed and implemented in Matlab® and is validated against measurement data from a distributed thermal response test (DTRT). The model is used to further analyze the test and to study the performance of the coaxial BHE for different operating conditions.

Furthermore, the influence of flow direction during heat injection and heat extraction are studied using a 490 m deep coaxial BHE which is simulated based on the undisturbed temperature profile