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Effects of the temperature distribution on the thermal resistance of double u-tube borehole heat exchangers

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ABSTRACT

The effects of the surface temperature distribution on the thermal resistance of a double U-tube Borehole Heat Exchanger (BHE) are studied by finite element simulations. It is shown that the thermal resistance of a BHE cross section is not influenced by the bulk-temperature difference between pairs of tubes, but is influenced by the thermal conductivity of the ground when the shank spacing is high. Then it is shown that, if the real mean values of the fluid bulk temperature and of the BHE external surface are considered, the 3D thermal resistance of the BHE coincides with the thermal resistance of a BHE cross section, provided that the latter is invariant along the BHE. Finally the difference between the BHE thermal resistance and the effective BHE thermal resistance, defined by replacing the real mean temperature of the fluid with the average of inlet and outlet temperature, is evaluated in some relevant cases.

1. Introduction

Ground-source heat pumps (GSHPs) are becoming a relevant technology for building heating and cooling, and for Domestic Hot Water (DHW) production. Indeed, the worldwide installed thermal power of GSHPs increased from 1.854 GW to 49.898 GW from 1995 to 2015 (Lund and Boyd, 2015). Ground-Coupled Heat Pumps (GCHPs) appear as the most promising kind of GSHPs, due to their applicability even where regional laws do not allow groundwater extraction. The most diffuse GCHP systems employ vertical ground heat exchangers, also called Borehole Heat Exchangers (BHEs). A BHE is usually composed of either a single U-tube or a double U-tube in high-density polyethylene, inserted in a drilled hole which is then sealed with a proper grout. A typical external diameter of each tube is 40 mm for single U-tube BHEs and 32 mm for double U-tube BHEs. The length of a U-tube BHE is usually between 50 and 150 m, and the most common diameter is about 15 cm.

Several procedures for the design of BHE fields are available in the literature. Kavanaugh and Rafferty (1997) proposed a method that has been recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2007). In this method, each BHE is sketched as an infinite cylindrical heat source and three heat pulses are considered, with durations of 10 years, one month and 6 h respectively. The interference between BHEs is taken into account through a temperature penalty coefficient. A more accurate method is the Earth Energy Designer (EED) software, developed by Hellström and Sanner (1997), which allows monthly simulations of any kind of BHE field for a long period, such as 50 years, and takes into account the effects of peak loads. A similar code is the GLHEPRO software developed by Spitler (2000). These codes employ dimensionless thermal-response functions called *g-functions*, whose expressions are not made explicit to the user. More precisely, a *g-function* is the dimensionless temperature, averaged along the BHE length, produced by a uniform and constant heat load per unit length, which acts on a BHE. The time variation of the heat load and the effects of the surrounding BHEs can be taken into account by the superposition of effects. Very accurate polynomial expressions of the *g-functions* have been determined recently by Zanchini and Lazzari (2013, 2014) and made available through tables of coefficients.

All the design methods cited above require the knowledge of the undisturbed ground temperature T_g, of the thermal conductivity k_g and of the thermal diffusivity α_g of the ground, as well as of the BHE thermal resistance per unit length.

Two definitions of BHE thermal resistance per unit length are usually considered in the literature. The first, that we denote by $R_{b,2D}$, refers to a BHE cross sections and is

$$R_{b,2D} = \frac{T_f - T_s}{q_l} \quad (1)$$

where T_f is the bulk fluid temperature in a BHE cross section (averaged between tubes), T_s is the mean temperature of the BHE surface in the same section, and q_l is the thermal power per unit length

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Nomenclature

c_p	Specific heat capacity at constant pressure (J kg^{-1} K^{-1})
d	Distance between centers of opposite tubes (m)
D_b	BHE diameter (m)
D_e	External diameter of tube (m)
D_i	Internal diameter of tube (m)
h	Convection coefficient (W m^{-2} K^{-1})
k	Thermal conductivity (W m^{-1} K^{-1})
k_x, k_y, k_z	Directional thermal conductivities (W m^{-1} K^{-1})
L	BHE length (m)
l_1, l_2	Closed lines in the xy plane
$\dot{m}$	Mass flow rate (kg s^{-1})
Nu	Nusselt number
p	Real coefficient
Pr	Prandtl number
$\mathbf{q}$	Heat flux density vector (W m^{-2})
$\dot{Q}$	Thermal power (W)
q_l	Heat flux per unit length (W m^{-1})
R_{11}, R_{12}, R_{13}	Thermal resistances (m K/W)
$R_{b,2D}$	Thermal resistance of a BHE cross section (m K/W)
$R_{b,3D}$	3D BHE thermal resistance (m K/W)
$R_{b,eff}$	Effective BHE thermal resistance (m K/W)
Re	Reynolds number
R_p	Thermal resistance of a polyethylene pipe (m K/W)
S_1, S_2	Surfaces (m^2)
T	Temperature (K)
T_f	Bulk fluid temperature (K)
$T_{f,ave}$	$= (T_{f,in} + T_{f,out})/2$
$T_{f,d}$	Bulk temperature of fluid going down (K)
$T_{f,in}$	Inlet bulk fluid temperature (K)
$T_{f,out}$	Outlet bulk fluid temperature (K)
$T_{f,up}$	Bulk temperature of fluid coming up (K)
T_g	Undisturbed ground temperature (K)
T_s	Temperature of the BHE external surface (K)
V	Portion of a solid (m^3)
$\dot{V}$	Volume flow rate (m^3/s)
x, y	Horizontal coordinates (m)
z	Vertical coordinate (m)
$\tilde{z}$	$z/10$, reduced vertical coordinate (m)
Z	z/L, dimensionless vertical coordinate

Greek symbols

α	Thermal diffusivity (m^2 s^{-1})
Θ_d	Dimensionless bulk temperature of fluid going down
Θ_{out}	Dimensionless bulk fluid temperature at outlet
Θ_u	Dimensionless bulk temperature of fluid coming up
μ	Dynamic viscosity (Pa s)
ρ	Density (kg/m^3)
(ρ c)	Specific heat capacity per unit volume (J m^{-3} K^{-1})
Σ_1, Σ_{12}	Dimensionless parameters, defined in Eq. (18)

Subscripts

1	of surface S_1, of fluid
2	of surface S_2, of BHE circumference
g	of ground
gt	of grout
m	Mean
p	of polyethylene
w	of water
_Z	Obtained by the method of Zeng et al. (2003)

exchanged between BHE and ground in the neighbourhood of that section, positive if supplied to the ground. If the thermal conductivity of the grout is known, $R_{b,2D}$ can be easily calculated by performing a 2D numerical simulation of the BHE cross section, or by employing approximate expressions available in the literature (Hellström, 1991; Bennet et al., 1987; Sharqawy et al., 2009). An analysis of the accuracy of the approximate expressions, for single U-tube BHEs, has been performed by Lamarche et al. (2010).

The second definition, called *effective* thermal resistance (Hellström, 1991), is

$$R_{b,eff} = \frac{T_{f,ave} - T_{s,m}}{q_{l,m}} \tag{2}$$

where $T_{f,ave}$ is the arithmetic mean of inlet and outlet fluid temperatures,

$$T_{f,ave} = \frac{T_{f,in} + T_{f,out}}{2} \tag{3}$$

$T_{s,m}$ is the mean temperature of the external surface of the BHE and $q_{l,m}$ is the mean thermal power per unit length exchanged between BHE and ground, positive if supplied to the ground. Expressions which relate R_{beff} and $R_{b,2D}$ are provided by Hellström (1991), for the cases of uniform temperature of the BHE external surface and of uniform wall heat flux from the BHE surface. Clearly, both cases are approximations of real conditions.

As pointed out by Lamarche et al. (2010), another possible definition is

$$R_{b,3D} = \frac{T_{f,m} - T_{s,m}}{q_{l,m}} \tag{4}$$

where $T_{f,m}$ is the real mean value of the bulk fluid temperature, namely

$$T_{f,m} = \frac{1}{2L}\left(\int_0^L T_{f,d}(z)\mathrm{d}z + \int_0^L T_{f,u}(z)\mathrm{d}z\right) \tag{5}$$

where L is the BHE length, z is the vertical coordinate directed downwards, $T_{f,d}$ is the local bulk temperature of the fluid going down, and $T_{f,u}$ is the local bulk temperature of the fluid coming up. Although Eq. (4) would be the natural 3D extension of Eq. (1), it is usually replaced by Eq. (2), because $T_{f,ave}$ can be easily measured.

The thermal resistance of a BHE is usually determined through a Thermal Response Test (TRT) performed as recommended by ASHRAE (2007).

In a TRT, first one measures T_g, as recommended by (ASHRAE, 2007) and (Gehlin, 2002). Then, hot water produced by electric resistances is circulated through the tested BHE, so that heat is injected into the ground. The basic monitored quantities are the heating power per unit BHE length, $q_{l,m}$, averaged along the BHE length, the inlet bulk fluid temperature, $T_{f,in}$, the outlet bulk fluid temperature, $T_{f,out}$, and the volume flow rate, $\dot{V}$. The evaluation of a TRT is usually performed by the infinite-line-source model, which employs as input data $q_{l,m}$ and a plot of $T_{f,ave} - T_g$ versus the natural logarithm of time t (Gehlin, 2002; Sanner et al., 2005; Signorelli et al., 2007). The slope of the plot is equal to $q_{l,m}/(4\pi k_g)$, and yields the ground thermal conductivity; the value of $T_{f,ave} - T_g$ for $\ln t = 0$ yields a relation between $q_{l,m}$, k_g, α_g and $R_{b,eff}$. Usually α_g is estimated and the relation is employed to determine $R_{b,eff}$. The value obtained is then usually interpreted as a value of $R_{b,2D}$.

As pointed out by Marcotte and Pasquier (2008), the thermal short-circuiting between the fluid going down and that coming up can cause a relevant difference between $T_{f,m}$ and $T_{f,ave}$, so that confusing $R_{b,eff}$ with $R_{b,2D}$ can yield a significant overestimation of the latter. Some studies on the real distribution of T_f along z and on the errors in the evaluation of $R_{b,2D}$ due to the approximation of $T_{f,m}$ with $T_{f,ave}$ were carried out in