

Multiple source ground heat storage

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Abstract. Sharing geothermal borefields is usually done with each borehole having the same inlet conditions (flow rate, temperature and fluid). The objective of this research is to improve the energy efficiency of shared and hybrid geothermal borefields by segregating heat transfer sources. Two models are briefly presented: The first model allows the segregation of the inlet conditions for each borefields; the second model allows circuits to be defined independently for each leg of double U-tubes in a borehole. An application couples residential heat pumps and arrays of solar collectors. Independent circuits configuration gave the best energy savings in a symmetric configuration, the largest shank spacing and with solar collectors functioning all year long. The boreholes have been shortened from 300 m to 150 m in this configuration.

Keywords: Ground source heat pumps, hybrid geothermal, geothermal model

1. Introduction

Ground source heat pumps, low temperature geothermal systems, are used in heating and cooling applications; mainly buildings. The Intergovernmental Panel on Climate Changes (IPCC) projects that the heat energy produced by ground source heat pumps will pass from 0.4 EJ/year in 2010 to 7.2 EJ/year in 2050 [1]. In cold climates, more heat is extracted from the ground during heating period than injected during cooling period. Hybrid systems are a solution for such issue.

Sharing a ground source heat pump borefields is becoming more common. Many buildings and processes with different heating and cooling loads profiles can share the same geothermal loop. It is possible, even preferable to couple complementary load profiles. An example of hybrid geothermal system would be to couple solar thermal collectors with heat pumps to a geothermal loop.

Nearly all available geothermal models consider only one inlet condition for all of the U-tubes and boreholes of a borefield, limiting the amount of possible configurations and control strategies to be evaluated. The objective of this research is to improve the efficiency of shared and hybrid geothermal systems by segregating heat transfer sources. This will be achieved by developing a semi-analytical model that considers independent inlet conditions for each borehole of a borefield in one part, and developing a model that considers independent circuits of double U-tubes in each borehole in second part.

In both models, the ground is modeled as a 2D diffusion control volume finite difference method. In the independent boreholes model, an analytical model based on thermal resistances is used to describe the heat transferred between the fluid and the borehole wall [2]. A second model is developed to describe the behavior of a double U-tube borehole where the two legs of the U-tubes are coupled to different sources [3]. It is a complement of an existing model [4, 5] that could simulate the same, in addition of having different capacitances in each leg.



Geothermal boreholes can be modelled in two main concepts: the borehole itself and the surrounding ground. Classical analytical ground models are: Infinite line source model [6], Infinite cylindrical source and Finite line source [7-9]. Many models are available to evaluate the borehole thermal resistance (R'_g): Paul [10]; Sharqawy [11]; Line-source [12]; Multipole [13, 14].

This paper will present both independent boreholes and independent circuits models and compare the performances of some configurations to a base case without solar collectors.

2. Independent boreholes

The proposed model is a semi-analytical model that evaluates temperature exchange between a fluid and the ground through geothermal boreholes.

The numerical part uses a 2-D control volume finite difference method (CVFDM) to solve the conduction problem in the ground. As a result, the problem is assumed to be independent of depth, L_p . A point-by-point Gauss-Seidel iterative method is used to evaluate the temperature field caused by diffusion in the surrounding ground. The analytical part of the model is composed of a Multipole borehole thermal resistance [14]. The link between the analytical and numerical parts is done with a shape factor, under a quasi-steady-state assumption.

For a ground assumed to involve constant thermophysical properties, the two-dimensional Cartesian heat conduction governing equation in a horizontal plane is based on Fourier's law:

$$\rho c_s \frac{\partial T}{\partial t} = k_s \left[\frac{\partial}{\partial x} \left(\frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial T}{\partial y} \right) \right] + S_T \quad (1)$$

The heat rate between the borehole heat exchanger and the surrounding ground is calculated from the heat transfer of the fluid passing through the U-tubes of the boreholes.

$$q = \dot{m}_f c_f (T_{f,in} - T_{f,out}) \quad (2)$$

The heat flux equation per unit depth between the borehole and the control-volume is then given by:

$$q' = \frac{Sf \times k_s}{L_b} (T_b - T_a) = \frac{(T_b - T_a)}{R'_c} \quad (3)$$

The thermal resistance analogy circuit is presented in **Figure 1**.

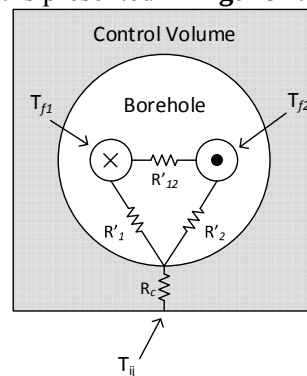


Figure 1. Combined borehole and shape factor thermal resistance analogy

The outlet fluid temperature $T_{f,out}$ is a function of the average ground temperature T_a . This temperature is evaluated from a weighted average of the eight ground control volume temperatures adjacent and contiguous for which the central control volume embeds a borehole, as depicted in **Figure 2**.

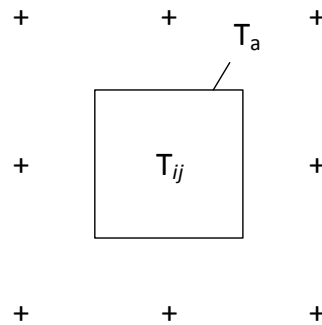


Figure 2. Ground temperature surrounding a source term

Hence, T_a is defined such that:

$$T_a = \left(\frac{T_n + T_e + T_s + T_w}{16} \right) + \left(\frac{T_{ne} + T_{se} + T_{sw} + T_{nw}}{16} \right) + \left(\frac{T_{i,j}}{2} \right) \quad (4)$$

The heat rate per unit length transferred from the fluid to the control volume surface (or conversely) can be expressed as a function of the inlet fluid temperature such that:

$$T_{f,out} = \frac{[(z-1)T_{f,in} + 2T_a]}{(1+z)} \quad (5)$$

Where dimensionless constant z is defined so that:

$$z = \frac{2\dot{m}_f c_f R'_{tot}}{L_b} \quad (6)$$

The model has been compared with the DST model [15, 16] in constant inlet conditions and variable inlet conditions with good agreement. The absolute difference between both models outlet temperature peaked at 0.15°C, with an average of 0.07°C on a global basis.

3. Independent circuits

Eslami-Nejad and Bernier [4, 5] were the first to model the thermal behavior of a borehole with two independent circuits. Their approach is a generalization of the Zeng et al. [17] method that was used to simulate a double U-tube configuration in parallel or in series. The proposed model is a contribution to Eslami-Nejad works, adding the possibility to change the angle between the circuits and simulation different capacitance and mass flowrates of fluid in each circuit. The physical problem is represented in **Figure 3**.

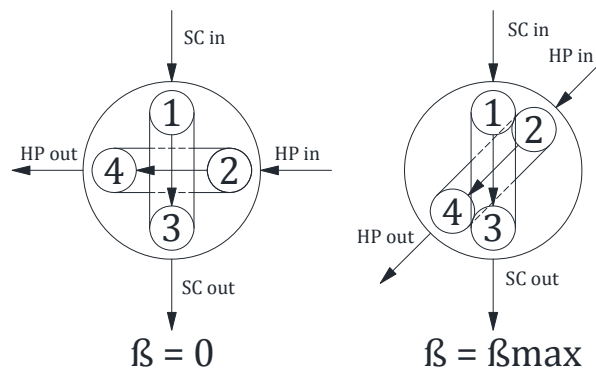


Figure 3. Independent circuit in symmetric (left) and non-symmetric (right) configurations

Eslami-Nejad and Bernier [5] showed that the above described configuration 1-3, 2-4 is the best for two reasons: heat transfer between the hot and cold fluid is better and the thermal short-circuit is reduced. One cannot argue with the second reason, since the distance between each leg of a circuit must be as far as possible. However, better heat transfer could be achieved if the pipes of the two independent circuits are closer, $\beta \neq 0$. The new model is presented in details in a paper [3]. In a very brief way, the energy balance would be

$$\begin{aligned} -\frac{d\theta_1}{dZ} &= a\theta_1 + b\theta_2 + c\theta_3 + d\theta_4 + e \\ -\frac{d\theta_2}{dZ} &= b\theta_1 + a\theta_2 + d\theta_3 + c\theta_4 + e \\ \frac{d\theta_3}{dZ} &= c\theta_1 + d\theta_2 + a\theta_3 + b\theta_4 + e \\ \frac{d\theta_4}{dZ} &= d\theta_1 + c\theta_2 + b\theta_3 + a\theta_4 + e \end{aligned} \quad (7)$$

where

$$\theta_i = \frac{(T_{f,i} - T_{f1,in}) + (T_{f,i} - T_{f2,in})}{T_{f1,in} - T_{f2,in}}, \quad T_{f1,in} \neq T_{f2,in} \quad i = 1, 2, 3, 4 \quad (8)$$

$$a = \frac{1}{S_1} + \frac{1}{2S_{12}} + \frac{1}{2S_{13}} + \frac{1}{2S_{14}}, \quad b = -\frac{1}{2S_{12}}, \quad c = -\frac{1}{2S_{13}}, \quad d = -\frac{1}{2S_{14}}, \quad e = -\frac{\theta_b}{S_1}$$

The model showed perfect match with the previous one and showed good agreement with a Runge-Kutta numerical method.

4. Application

A TRNSYS model couples residential heat pumps with solar collectors to the same borefield. The objective is to present the effect on energy consumption of heat pumps for different hybrid geothermal borefield configurations.

Three main configurations are compared to a base case without solar collectors: a classic mitigated loop, independent boreholes and independent circuits. A detailed hourly simulation is executed over three years to compare the solutions. The geothermal borefield is composed of 12 boreholes for 12 residential building heat pumps. Solar collectors with a surface of 24 m² are installed for each residential building. The **Figure 4** shows a single residential building thermal load.

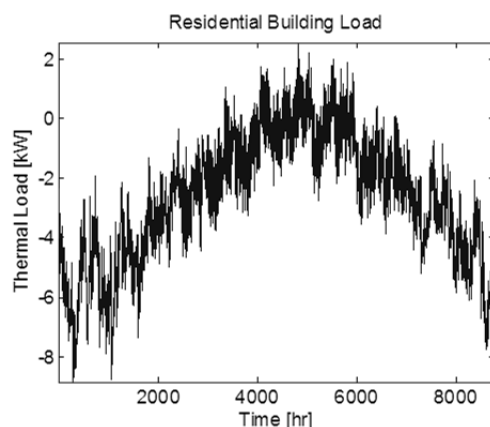


Figure 4. Residential thermal loads

The thermal loads are largely unbalanced. This would result in a reduction of the performances of the ground source heat pump system through time. The **Figure 5** shows a diagram of the mitigated loop configuration.

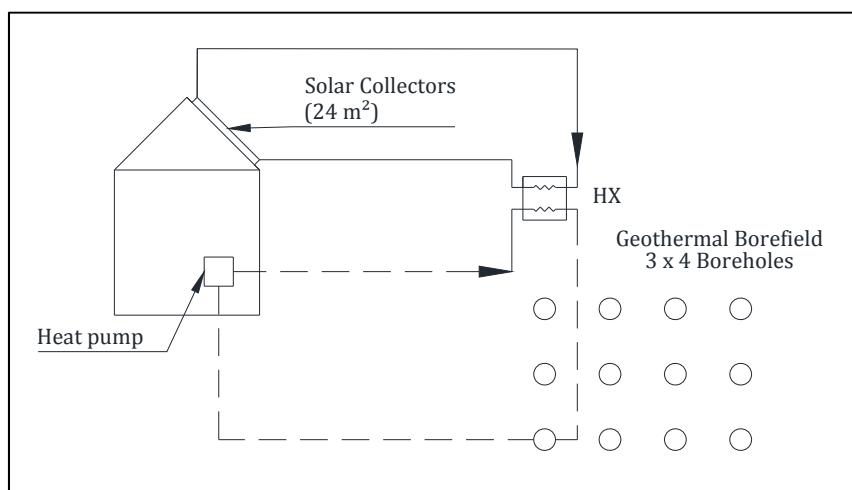


Figure 5. Mitigated loop configuration

This configuration and the base case can be modelled with known models, such as DST, but the next ones cannot. An independent borehole in central configuration is shown in **Figure 6**.

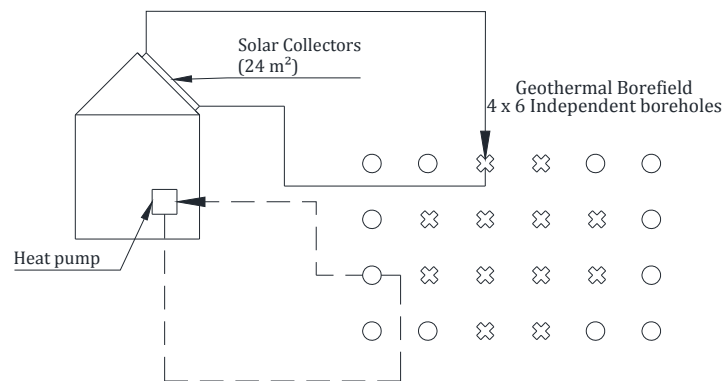


Figure 6. Independent boreholes, central configuration

In this configuration, the heat from the solar collectors is injected in the centre of the borefield and the heat pumps are coupled to the outer boreholes. The **Figure 7** shows a different configuration of the independent boreholes: the staggered configuration.

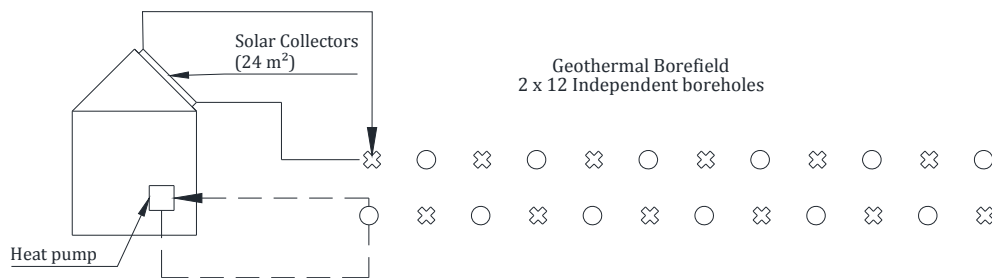


Figure 7. Independent boreholes, staggered configuration

In this configuration, the heat pump and residential circuits are closer to one another than with the centre configuration. The **Figure 8** presents independent circuit the non-symmetric configuration.

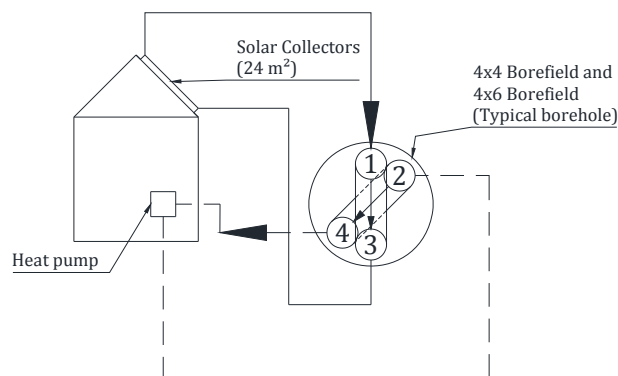


Figure 8. Independent circuits, non-symmetric configuration

The symmetric configuration is the same, except for the angle between legs of the U-tubes, which are equally spaced, as presented in **Figure 3**.

The simulations used two control strategies: one where the solar collectors loop does not function during summer (no sum) and the other where they function all year long (all year). There are also two leg spacing configurations compared: Type A and Type C, shown in **Figure 9**.

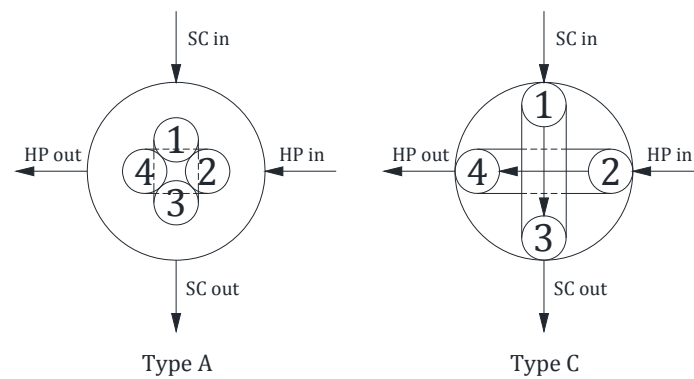


Figure 9. Spacing of Type A (left) and Type C (right)

The energy consumption of each heat pump for a three years of simulation are presented in Table 1.

Table 1. Single heat pump energy consumption [kWh].

BHE	Configurations	Type	Ctrl	Energy HP	Savings
3x4	Base	C	-	10884	-
3x4	Mitigated	C	All year	10771	113
3x4	Symmetric 150m	C	All year	10675	209
3x4	Mitigated	C	No sum	10621	263
3x4	Non-symmetric	A	All year	10501	383
3x4	Symmetric	A	No sum	10334	550
3x4	Symmetric	C	No sum	10222	662
3x4	Non-symmetric	C	All year	10201	683
3x4	Non-symmetric	C	No sum	10190	694
3x4	Symmetric	C	All year	10184	700
4x6	Central 6m	C	All year	10670	214
2x12	Ind staggered 6m	C	All year	10651	233
2x12	Ind staggered 3m	C	All year	10622	262
2x12	Ind staggered 4.5m	C	All year	10619	265
4x6	Central 4.5m	C	All year	10614	270
4x6	Non-symmetric	A	All year	10066	818
4x6	Non-symmetric	C	All year	9877	1007

The electrical energy consumption of the heat pumps over a three years simulation of the base case is 10884 kWh. The best savings of the 12 BHE simulations has been achieved with the independent circuits with Type C shank spacing. The symmetric and non-symmetric parameters did not show much advantage; neither did the all year and no sum control strategies. With the all year control strategy, the ground temperature tends to rise over the years, which would be beneficial on the heating mode of the heat pump, but would be disadvantageous in cooling mode. For the 24 BHE configurations, the independent circuits also have shown the best savings. The independent boreholes configurations required twice as much boreholes as the independent circuits with less energy savings. The independent circuits symmetric Type C All Year configuration has allowed to cut in half the length of the boreholes and keep fluid temperatures above 0°C.

5. Conclusion

Hybrid ground source heat pump systems are useful when the thermal loads on the borefield are unbalanced. Two models have been developed to segregate circuits of hybrid systems. The first one allows simulating geothermal borefields with independent inlet conditions for each borehole. The second allows separating the circuits in two different legs of double U-tubes. In a residential heat pump/solar collector application, the independent circuits, Type C, all year control strategy configuration has given the most energy efficient results. It has allowed the boreholes to be shortened from 300 m to 150 m.

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6. Nomenclature

c	Fluid specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)
d	diameter (m)
h	heat transfer coefficient, ($\text{W m}^{-2}\text{K}^{-1}$)
k	thermal conductivity ($\text{W m}^{-1}\text{K}^{-1}$)
L	Length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
q	Heat extraction/injection rate (W)
r	radius (m)
ρ	Density or specific weight (kg m^{-3})
R	Thermal resistance ($\text{W m}^{-1} \text{K}^{-1}$)
R_c	Shape factor equivalent thermal resistance
S	modified thermal resistances
S_f	Shape factor between borehole and control volume boundaries
S_T	Source term
T	temperature ($^{\circ}\text{C}$)
W	Control volume width used in shape factor definition
Z	dimensionless depth
α	mass flow ratio
β	angle of rotation (deg)
θ	non-dimensional temperature
Δ	delta circuit

Subscripts

1	Inlet leg of 1-3 Circuit
2	Inlet leg of 2-4 Circuit
3	Outlet leg of 1-3 Circuit
4	Outlet leg of 2-4 Circuit
a	Average
b	Borehole
c	related to the thermal resistance between the borehole and its control-volume
f	Fluid
g	Grout
s	Ground
tot	Total
in	inlet
out	outlet
n,s,e,w	North, South, East, West neighbors of node i,j
ne, se, nw, sw	North-east, South-east, North-west, South-west
f	mean fluid
f_o	fluid outlet