NUMERICAL SIMULATIONS OF VERTICAL UNDERGROUND HEAT EXCHANGERS FOR HEAT PUMP APPLICATIONS

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ABSTRACT

Ground heat pumps use the ground as heat source/sink reservoir for space heating/cooling of buildings. The key components in these systems are the ground heat exchangers, their design is critical to achieve an optimal thermal performance not only for the short term but also for the long term exploitation. The present paper presents a thermal analysis of domestic multi-boreholes heat exchangers connected in series at shallow depth. Numerical simulations have been carried out using TRNSYS software taking into account local meteorological data. Flow direction of the water entering the underground secondary loop is inversed at regular interval in order to equilibrate the ground temperature nearby the different boreholes. This method is shown to be efficient to keep almost constant ground reservoir temperature by permitting a good heat recharge especially for the long term system exploitation. The conventional method (flow in one direction only) might cause in some cases performance degradation, due to the formation of an unbalanced ground temperature surrounding the different boreholes particularly after several years of intensive utilization and when the boreholes separation is smaller than recommended minimum distance. This study also illustrate the importance of taking into account a daily and annual schedule for system operation, the pump off's periods are crucial for the natural heat recovery of ground reservoir resulting on higher performance and longer system life.

Keywords: Ground-coupled Heat Pump, Ground storage temperature, U-tube heat exchangers, multi-boreholes.

1. INTRODUCTION

In last decades an increasing number of residential and commercial buildings have chosen to be equipped with ground-coupled heat pumps for space heating, cooling and hot water supply. These systems have been recognized to provide viable, environment-friendly alternatives to air heat pump systems.

This is probably due to the fact that ground temperature at a certain depth remains nearly constant throughout the year which can be attractive from thermodynamic point of view. Resulting on improving the performance of the system and the capacitance of the soil is considered as a potential source or sink medium for heating and cooling of buildings.

However, the ability to predict both the long-term and short-term behavior of ground loop heat exchangers is critical to the efficient design and energy analysis of ground source heat pump systems. Numerical simulation has become a strong tool to perform thermal analysis of ground coupled heat exchangers and several articles can be found in literature. However very few of them deal with the long-term impact on the mean ground temperature resulting from the thermal interaction between the borehole heat exchangers and the ground heat source/sink medium.

In the following sections, a case study of multi borehole is described and implemented in TRNSYS software for multi year simulation. Different parameters are presented in brief and the results of application of a new method in order to homogenize the ground temperature for multi boreholes system are discussed.

2. MODEL DESCRIPTION

The multi-borehole heat exchanger system has been studied using a detailed 3D model incorporated in the TRNSYS software. Figure 1 illustrates the schematic configuration of the underground secondary loop of the studied case. It's composed of three boreholes related in series. Each borehole contains single U-tube made of HDPE material, boreholes are filled with cement. A heat carrier fluid (water) is circulated through the ground heat exchangers and either rejects heat to/or absorbs heat from the ground depending on the temperatures of the inlet fluid which are determined by the annual schedule for heating and cooling demand.

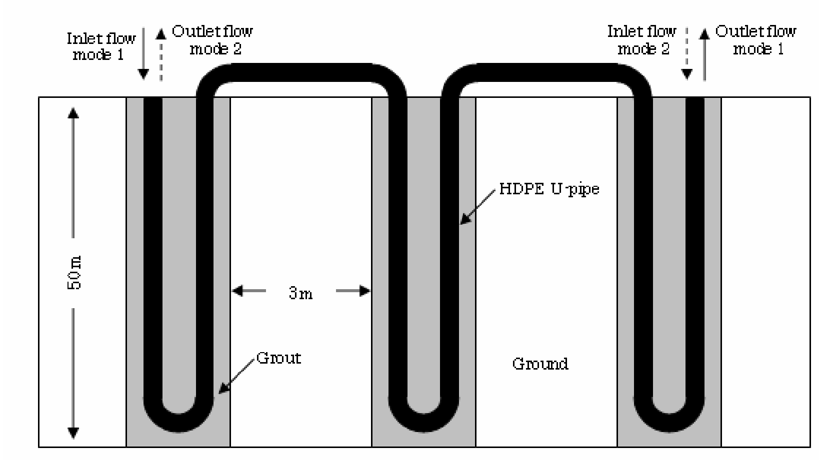

Fig.1 Schematic diagram of multi-boreholes ground heat exchangers

This TRNSYS subroutine models a vertical heat exchanger that interacts thermally with the ground. The model is based on finite volumes method and accounts for the thermal properties of the fluid, pipes, backfill and surrounding ground. Table1 below describes the thermal properties of the different material.

Table1. Thermal properties of material

Water	Density Specific heat	(Kg/m^3) (KJ/Kg.K)	1000 4.190
Pipe	Conductivity	(W/mK)	0.42
Fill material	Conductivity	(W/mK)	1.95
Soil	Conductivity Heat Capacity	(W/mK) (KJ/Kg.K)	1.6 3.444

There is convective heat transfer inside the heat exchangers pipes and conductive heat transfer to the storage volume (no underground water). Assuming that there is no thermal resistance at the different interfaces and the soil is homogenous. The initial ground temperature of the surrounding ground and the far field ground temperature are calculated using Kusuda correlation, the latter takes into account the annual and the daily fluctuations of the ground temperature according to a specific meteorological data file of the studied site.

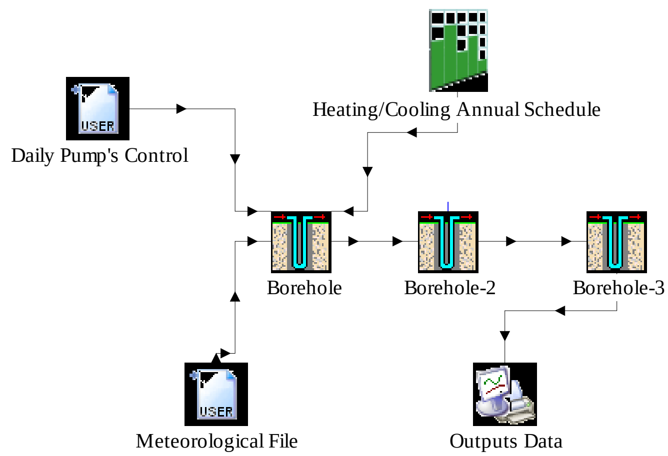

Fig2. Project in the TRNSYS simulation studio workspace

Figure 2 shows a part of the project's configuration under TRNSYS simulation studio, the annual schedule module control the inlet fluid temperature to first borehole depending on cooling and heating season in the year. The daily pump schedule module control the operating time of the secondary loop. The pump operates 16 hours/day. A meteorological file is connected to the boreholes subroutines providing air temperature values at each time steps. This input serves to calculate ground distribution at far field boundary conditions and deep soil temperature.

Table2. Physical parameters of the multi borehole heat

Borehole Diameter (mm)	150
Pipe Inner Diameter (mm)	25
Pipe Outer Diameter (mm)	30
Pipe Legs Spacing (mm)	50
Number of boreholes	3
Boreholes Spacing (m)	3
Boreholes Depth (m)	50
Water Flow Rate (Kg/s)	0.3
Water inlet temperature (^{o}C) (Heating mode)	4
Water inlet temperature (^{o}C) (Cooling mode)	28

Simulations are carried out over periods up to 5 repetitive years. For that, an appropriate time step of 0.1h was chosen accordingly to a compromise between calculation speed, stability and precision. At each time step the borehole model reads the new temperature at top surface (from meteorological file) and calculates the far field boundary temperature (using Kusuda ground correlation). Constant inlet temperatures (see table2) are set depending on the cooling/heating loads and the operation of the heat pump is managed by a daily and seasonally defined schedule. In addition, a thermostat controls the heating or cooling modes of the heat pump based on the outside temperature variation through a typical meteorological year.

In addition to the different physical parameters described in table 1 and 2, the model will be able to calculate new outlet temperature leaving each borehole and means ground temperatures within different radius from each borehole. Note that following the scheme shown in figure1 and 2, the outlet fluid temperature of borehole 1 corresponds to inlet temperature of borehole 2 and the outlet fluid temperature of borehole 2 corresponds to inlet fluid temperature of borehole3.

Here below, figure 3 shows the heating (red) and cooling (bleu) periods of the year and thermostat set points for air temperature of a typical year in the region of Tokyo. It's clear that the periods for heating are higher than for cooling during one typical year.

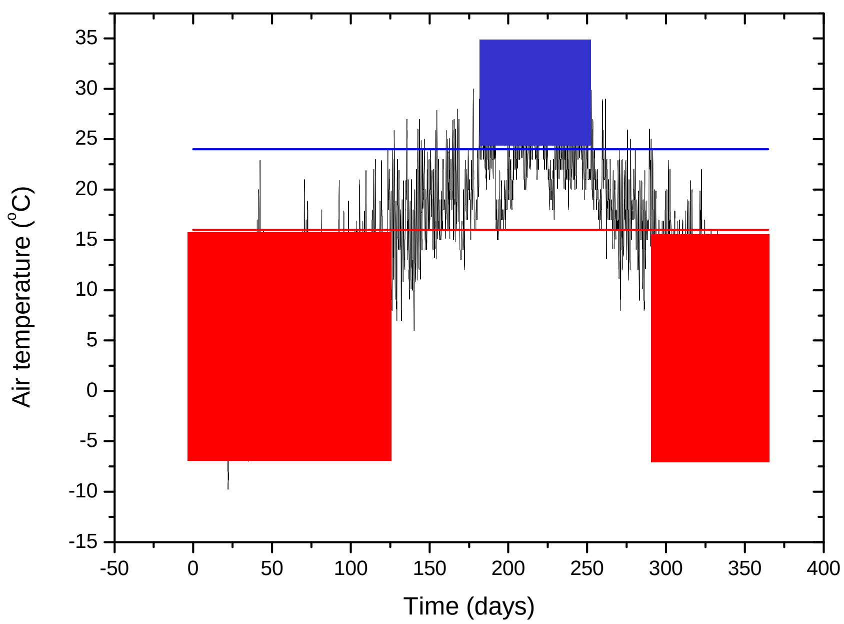

Fig3. Annual heating/cooling schedule according to Tokyo air temperature

4. RESULTS AND DISCUSSIONS

In this section, simulation results for five years of the two methods for flow directions are presented and discussed

4.1 Conventional method (Mode 1):

The conventional method consists on circulating the water flow only in one direction throughout the heat exchangers that are set in series (see fig.1)

Figure 4 shows the evolution of the calculated yearly mean ground temperature within one meter radius of each borehole. The decrease of the ground temperature nearby borehole 1 from the initial ground temperature is significant compared to ground temperature borehole 2 and 3. After five years operation the mean ground temperature within 1m radius of borehole 1 is almost 4degres lower than initial ground temperature. This difference is due of the cool fluid temperature entering borehole 1 compared to others boreholes. Also, considering the important heating loads compared to the cooling loads (see fig.3). Unbalanced loads results on poor heat recharge of the ground reservoir near the borehole 1. This situation might be worse after several years operation, especially when boreholes are not enough spaced.

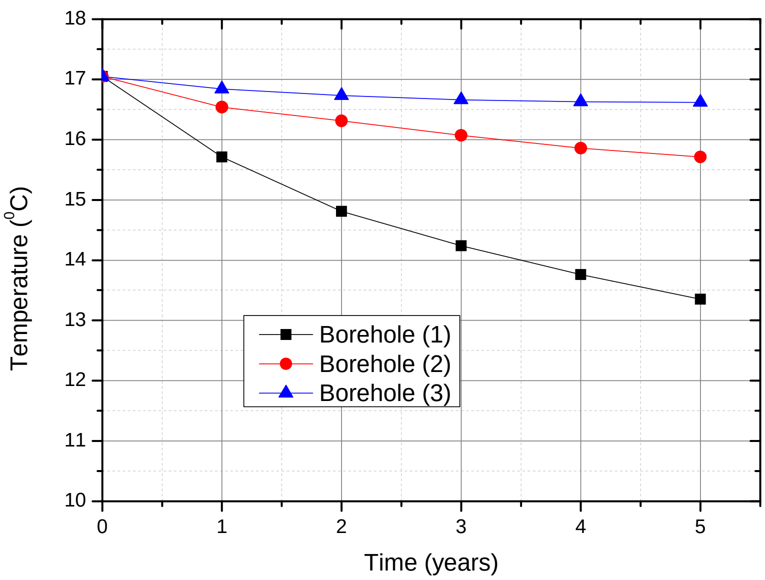

Fig4. Yearly mean ground temperature within 1m radius from boreholes (mode 1)

To remedy to this problem, the following method is proposed

4.1 Switching mode method (mode 1/ mode 2):

In this method, the flow direction of the water entering the underground heat exchangers is inversed at regular intervals (every 3 days).

Mode 1: fluid entering at borehole 1 and leaving from borehole 3
Mode 2: fluid entering at borehole 3 and leaving from borehole 1

Variations of yearly mean ground temperatures nearby boreholes are illustrated in figure 5. It is clear that ground temperature within one meter radius of the different boreholes has increased compared to the conventional method; this can be explained by the homogeneous distribution of heating/cooling loads when inversing flow at regular intervals. Permitting at the same time an efficient natural recharge of the ground particularly during the OFF periods of the water pump (after the heating season and during the cooling periods).
Ground temperature profiles nearby borehole 1 and 3 are -as expected- almost perfectly corresponding due to the balanced method applied to the both boreholes. However the ground temperature nearby borehole 2 is slightly higher than boreholes 1 and 3 this is due to the lower temperature of fluid entering borehole 2 which corresponds to the leaving fluid temperature from borehole 1 or 3 depending on the mode.
This method is highly efficient to stabilize ground temperature for in series multi boreholes systems. Allowing almost constant temperature distribution in the ground reservoir. This results on better heat recovery and more efficient heat extraction/rejection in the ground.

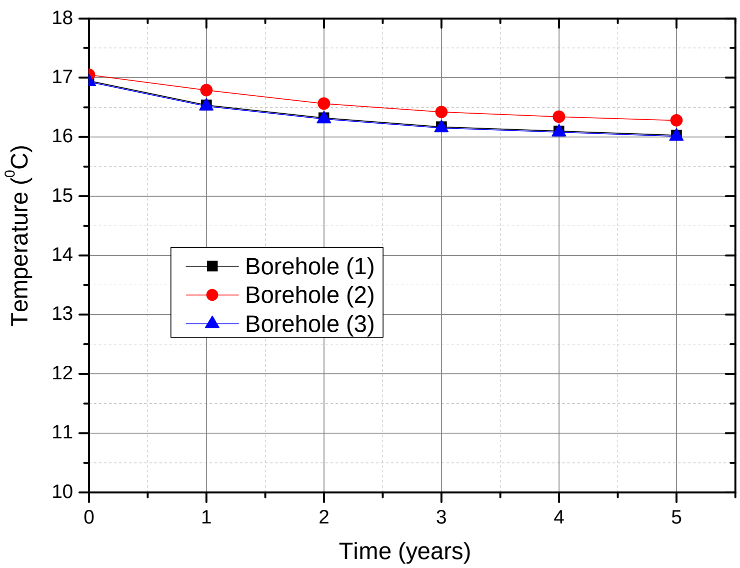

Fig5. Yearly mean ground temperature within 1m radius from boreholes
(Switching mode 1 and 2)

Figure 6 shows the variation of the mean ground temperature (green) within one meter radius of borehole 1, the outlet fluid temperature (red) from the same borehole is also illustrated which represents the thermal response to the inlet temperature impulsions (bleu). Here the ground temperature decreases slightly during these 10 days heating. In the off periods, the temperature of the fluid remaining in the borehole pipes has tendency to increase but falls as soon as the pump starts to work again.

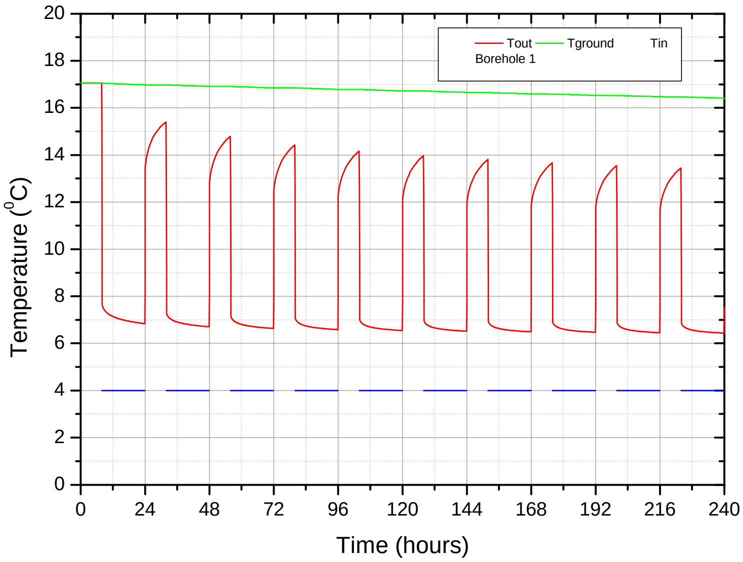

Fig6. Ground and outlet fluid temperatures variations.

5. CONCLUSION

This study reports the significant thermal benefit using the reverting flow direction method at regular intervals in order to equilibrate the ground reservoir temperature for multi boreholes. It has been shown that when using the conventional method (mode 1 only) the mean ground temperature within 1meter surrounding the first borehole decrease by more than 4^{o}C compared to the last borehole after 5 years system operation, this affect directly the outlet fluid temperature. However using switching method (mode 1 and 2) with 3 days intervals remedy to this thermal unbalance giving almost homogenous ground temperature nearby the different boreholes and constant outlet fluid temperature.

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