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NUMERICAL ANALYSIS OF THE UNDERGROUND WATER FLOW ON THE BOREHOLE HEAT EXCHANGERS PERFORMANCE

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Abstract

The objective of present work is to performed long-term analysis of the BHE focus on the effect of the underground water flow on the borehole heat exchangers performance. The mathematical model of the flow and heat transfer in borehole heat exchanger and surrounding area has been constructed. For present study the underground water flow has been model in 10 or more meter thick horizontal layer located at few tested levels under surface. Four flow speeds has been considered. Flow speed of U_g=2,0; 20,0 and 200,0 m·year^{-1}, and 2.67 m·day^{-1} which represents all range types of flow diffusion dominated, mixed flow and convective dominated flow. In presented paper different but realistic scenario possible to occur and taking in the account most important and typical parameters like rock formation, construction of the borehole heat exchangers, heat pump model, working parameters (circulation rates), and thermal load will be presented. Experimental TRT data versus numerical data will be also presented.

Key words: heat exchangers, reservoir engineering, heat pumps systems, borehole heat exchangers

INTRODUCTION

One of the important issue in the designing borehole heat exchangers (BHE) is the long-term performance of the system. The performance directly reflect the economical profitability and depend on large number of construction and working parameters.

The objective of present work is to performed long-term analysis of the BHE focus on the effect of the underground water flow on the field temperature which is linked to the borehole heat exchangers performance. The mathematical model of the flow and heat transfer in borehole heat exchanger and surrounding area has been constructed. For present study the underground water flow has been model in the interval between 3-15 [m] under the top surface. Four flow speeds has been considered. Flow speed of U_g=2,0; 20,0 and 200,0 m·year^{-1}, and 2.67 m·day^{-1} which represents all range types of flow diffusion dominated, mixed flow and convective dominated flow. Typically BHE system depend on large number of parameters like rock formation, construction of the borehole heat exchangers, heat pump model, working parameters (circulation rates), thermal load will be but here the focus is on the ground water flow mainly. In soils in areas of groundwater flow, the thermal energy transport due to convection as well as their interaction with the solid material has to be consider in numerical modelling of borehole heat exchangers system. Even for the cases of small interval and very low velocity of groundwater flow of about 1,0 m·year^{-1}, the role of convective heat transport cannot be completely neglected. An increase of the BHE system performance due underground water flow can be large.

In any that type geothermal system independent of construction and deep of BHE the amount of heat possible to transferred from the soil to heat pump system need to be carefully analyzed. Otherwise efficiency of the system with the time may be seriously decreased due to not completely system regeneration. Degradation in performance may occur temporary or permanently and results in total efficiency of the system much lower in comparison when system was new and the soil has original temperature profile. Possible ground freezing can be so serious that can damage outer tube permanently or can increase thermal contact (micro-space) which increases thermal resistance between borehole tubes and soil. In that cases underground water flow can usually guarantee soil regeneration and prevent lost of efficiency with the time. In present paper analysis has been to study heat transfer in the field consist of five borehole heat exchangers and the surrounding soil. Focus is on the long-term temperature distribution in the soil containing underground water flow.

NUMERICAL MODEL

The governing energy equation for the three dimensional unsteady heat transport in geothermal system consist of five borehole heat exchangers presented in Figure 1 are solved for the soil (consider as a domain 1) and in boreholes heat exchangers (domains 2). The details about of BHE tubes construction and dimension, fluid properties and soil properties are presented in table 1.

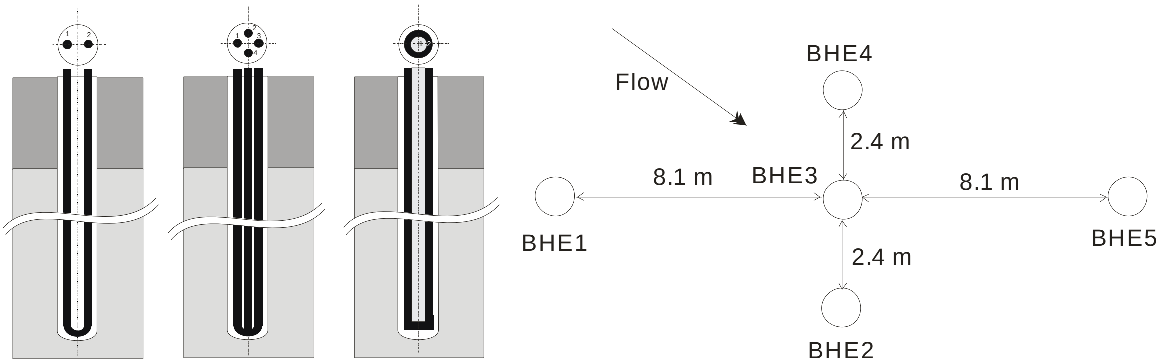

Figure 1: Experimental test field at AGH University Campus

The governing energy balance equation for the three dimensional unsteady heat transport in geothermal system takes for the soil form:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + s \tag{1}$$

where: ρ, c_p, k are the physical properties of the soil formation – density, specific heat and heat conductivity. Source term s allow to take into consideration other effects in soil like underground water flow, natural heat sources or phase changes.

Assuming no chemical reaction and phase change in working fluid energy balance equation for first sub-domain (borehole with heat exchangers) can be described as:

$$\rho c_f \frac{\partial T}{\partial t} + \rho c_f \mathbf{v} \cdot \nabla T = \nabla \cdot (k_i \nabla T) + s \tag{2}$$

With the mathematical model and numerical procedures we study the system performance depended on soil formation properties, heat exchangers type (Coaxial, single U-tube and double U-tube) and total power. The temperature of the surface has been varying with time according to realistic weather condition. Heat exchanger tubes (H=78 m) were initially filled with water with thermal equilibrium of the soil formation. The working fluid was 30% water solution of glycol. Simulation time was set up 10 years. The variance of the thermal power per borehole has been presents in figure 2. At initial time *t* soil has a temperature profile presented in figure 3 (right) and then desired power has been applied and every year has identical thermal power distribution. Total amount of energy transferred from soil to the surface ground pump system was 17,5 MWh/year /borehole

Table 1. Dimensions of BHE tubes, fluid properties and soil properties

Construction of BHE		Parameter	Value
	D	Borehole diameter	0.143 m
	H_w	Borehole depth	78.0 m
	ρ_f	Fluid density	1021.0 kg/m^3
	k_f	Fluid heat conductivity	0.7 W/(mK)
	c_{pf}	Fluid specific heat	3906 J/(kgK)
	ν	Viscosity	4.16*10^{-6} m^2/s
Coaxial (BHE1)	D_z	Outer tube outer diameter	0.0582 m
	D_w	Outer tube inner diameter	0.053 m
	d_z	Inner tube outer diameter	0.04 m
	d_w	Inner tube inner diameter	0.0348 m
Single u-tube (BHE2, 3, 4)	d_z	u-tube outer diameter	0.04 m
	d_w	u-tube inner diameter	0.0352 m
Double u-tube BHE5	d_z	u-tube outer diameter	0.032 m
	d_w	u-tube inner diameter	0.0272 m

Soil properties		
formation type	Thermal conductivity	Heat capacity
	W/(mK)	MJ/(m^{3}K)
Soil type I	1,373	2.33
Soil type II	2,025	2,29
Soil type III	5,132	2.59

For the pipe following material properties have been set 912 kgm^{-3}, 1200 J/(kgK), 0.45 W/(mK) as density, specific heat and conductivity. The space between outer tube and soil has been fully filed with cement with the thermal properties: density ρ_c=2180 kg/m, specific heat c_{pc}=1130 J/(kgK) and conductivity k=1.2 W/(mK) (2.0 for BHE3 and 1.8 for BHE4). Working fluid flow rate was q=20 l/min (per borehole). All properties are assumed to be constant (except for soil for cases when water friezing occurs in soil and properties of ice are introduce). The presented system cold fluid with temperature T_{in} was injected down the BHE (inner tube in coaxial heat exchangers, U-tube, two of U-tubes) and leave tubes (hotter) with outlet temperature T_{out}. For condition presented here soil is consider as one or two phase porous material (30% saturation) in which underground flow at interval from 3-15 m under top surface may occur. The details about mathematical description and numerical procedure can be found in [5].

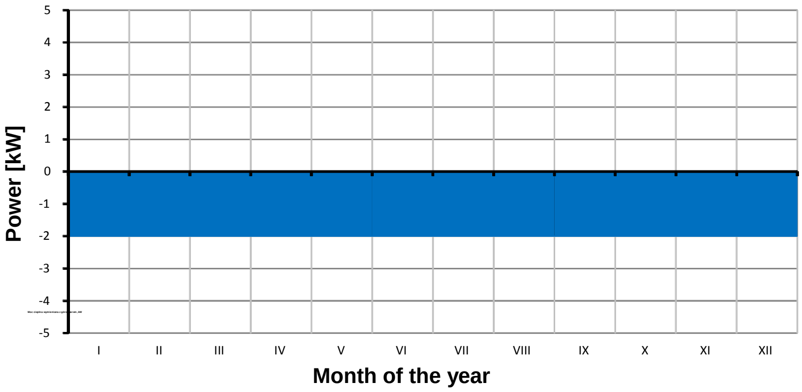

Figure 2: Power profile of BHE load per each BHE

To solve model equations (1)-(2) control volume method has been used on cartesian grid. For approximation of the unsteady terms two-level method has been used. For the convective/diffusive terms central difference CDS or hybrid method has been used. Time step was not constant during computations but varied in range from $\Delta t_{min}=60$ to $\Delta t_{max}=7200$ s to performed optimal accuracy at any time. Grid size used here was 200x200x100 control volumes (Nx*Ny*Nz) for domain of size 130x130x130 m. The borehole heat exchange and near borehole area (up to 50D) was locally much finer grid (up to 50 times) to accurately approximate heat exchangers. This was realized using *local grid refinement* technique with iterative convergence procedure. Validation was performed for several cases. For the test case with unsteady infinite linear source the temperatures compare to analytical solutions differs less than 0.1%. Experimental validation has been also performed and the results are presented in next section.

EXPERIMENTAL AND NUMERICAL RESULTS

With the mathematical model and numerical procedures described in previous section the parametric study of soil formation properties and power consumption influence on the effluent temperature has been preformed. Inlet temperature T_{in} is calculated as a results of desired power at any time (negative power mean that the heat is transfered from the soil to heat pomp and the outlet temperature T_{out} is a results of inlet temperature and heat exchange with the soil. The boundary conditions on the side walls of domain are adiabatic, top surface has realistic weather condition and bottom has natural the Earth heat flux 10 mW/m^2. The initial temperature T_{init} was obtain from the measurement of the soil and is it presented in figure 3(right). Heat exchanger tubes were initially filled with water with thermal equilibrium of the soil formation. At initial time t=0 pomp start working with flow rate 20.0 l/min. In the case of double U-tube (BHE no. 5) flow rate was two times smaller and total power was distributer over two U-tubes). Simulation time was set up t=10 years.

Validation

In figure 3 (right) comparisons between experimental data and numerical simulation for thermal response test (TRT) performed on the BHE no 4 in Geoenergetics Laboratory of Drilling and Geoengineering Department of AGH University of Science and Technology in Krakow has been presented. Taking in account large amount of important parameters (not easy to determined) comparisons shows that all parameters as well and mathematical model and numerical procedures has been set up properly.

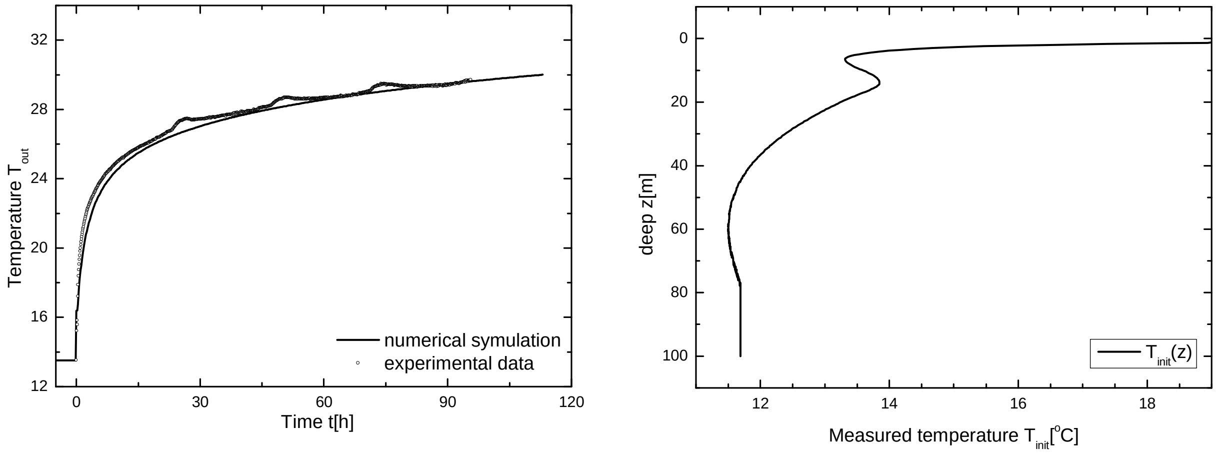

Figure 3: Numerical and experimental data for TRT test(left) and T_{ini} initial profile (right)

Heating soil

Before the full log term soil exploration was performed test similar to TRT has been done. In this case the inlet temperature T_{in} was constant and equal 32^{o}C. Results after 100 days of continuous work for BHE1 are presented in figure 4 and 5. In figure 4 temperature profile inside of heat exchangers tubes is plotted for soil I and soil III. The hot fluid with temperature T_{in} is injected down the annulus of the heat exchanger and let it flow up in central tube with outlet temperature T_{out}. When working fluid starts flowing down it decreases temperature until bottom part of BHE. Then when flowing up small increase in its temperature due to contact with hotter external tube can be seen. Depending on soil parameters outlet temperature is around 26 ^{o}C for soil I and 23 ^{o}C for soil III. In both cases increase in temperature in reference to bottom temperature T_{den} is around 2^{o}C. In this figure two notation for soil can been seen – soil I (layer) model is constructed [5] as a multi layer model where each layer was certain size and thermal properties. Soil I_{ave} model has only one layer of the mean properties of multi laver model. For presented cases both models gives very similar results unless small difference can be notice.

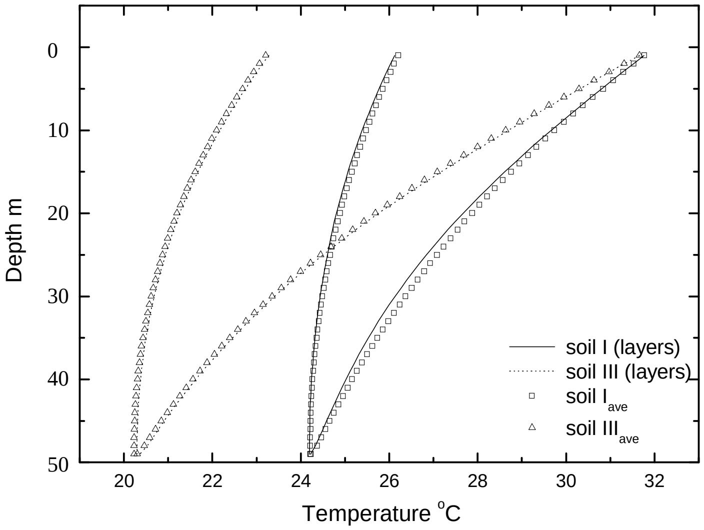

Figure 4: Temperature of the fluid inside BHE tubes at time t=100 days, for soil I and III

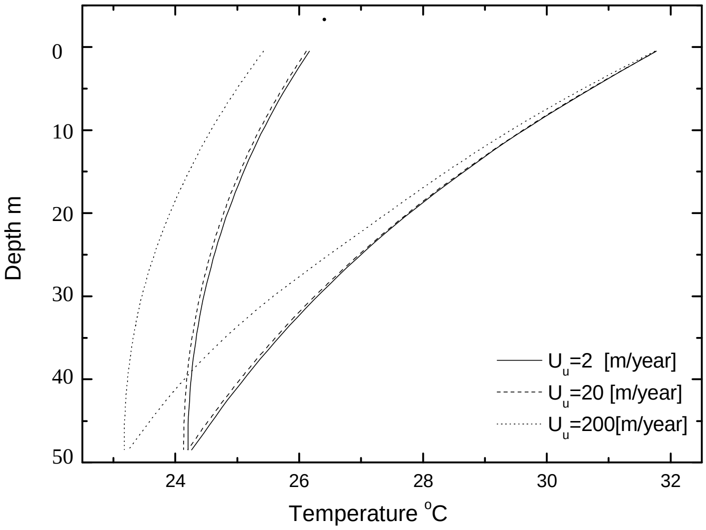

Figure 5: Temperature of the fluid inside BHE at time t=100 days, soil formation type I and for three speeds of underground water flow

In figure 5 similar temperature profile across heat exchangers has been shown for case of soil I and underground water flow in occurring in small interval of soil (3-15m). Effect for velocity higher than 20.0 m/year ($6.3*10^{-7}$ m/s) can be notice and for 200 m/year is quite large. Almost the same effect will give computation in much better conducted soil II. It has to be notice that interval of flow is only 11m and in comparison to length of BHE this is only 14%. For the first two values of speed of underground water U_g=2,0 and 20,0 m·year^{-1} differences in outlet temperature is very small. Diffusion in soil has strong effect. For the speed U_g=200,0 m·year^{-1} results differ reasonable in reference to case without underground flow. For soil with low conductivity flow effect is larger than for the soil with higher one.

Soil Exploration

In figure 6 and 7 contour of temperature in the soil is presented in vertical cross-section containing three of five borehole heat exchangers (no. 1, 3and 5). Influence of underground flow in relatively short interval on temperatures can be seen. The results of the simulation show that borehole heat exchangers are influenced by geological conditions as well as heat exchanger type.

On the figures 7-12 there are temperature distributions around of boreholes no. 1, 3 and 5. The crossection is at a depth of 9 m. The two cases is presented on every figure, in case of no underground flow (right) and with underground flow (left) after 2, 4, 6, 8 and 10 years of operation.

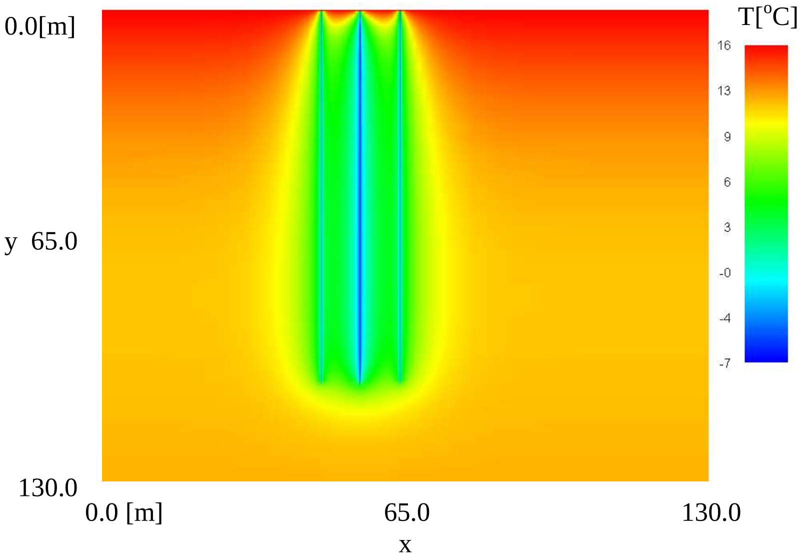

Figure 6: The temperature distribution of the rock mass in the vertical plane passing through the axis of borehole heat exchangers (1, 3, 5) after 2 years of operation without water flow in the aquifer

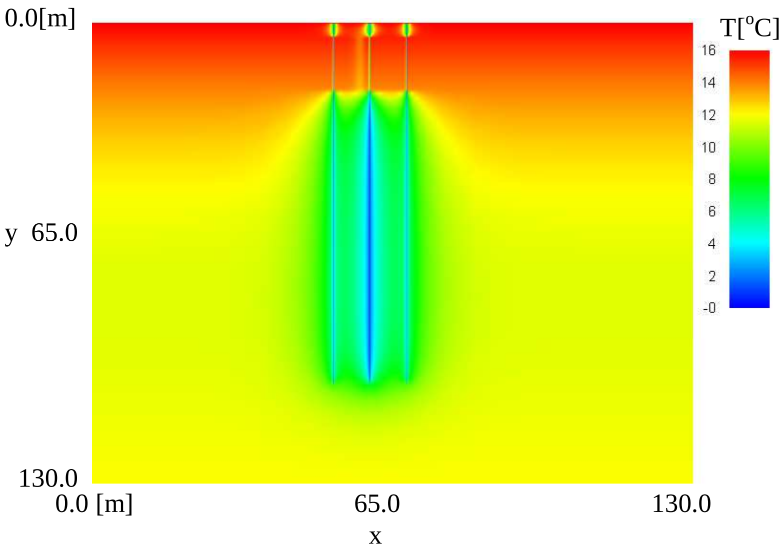

Figure 7: The temperature distribution of the rock mass in the vertical plane passing through the axis of borehole heat exchangers (1, 3, 5) after 2 years of operation with water flow in the aquifer

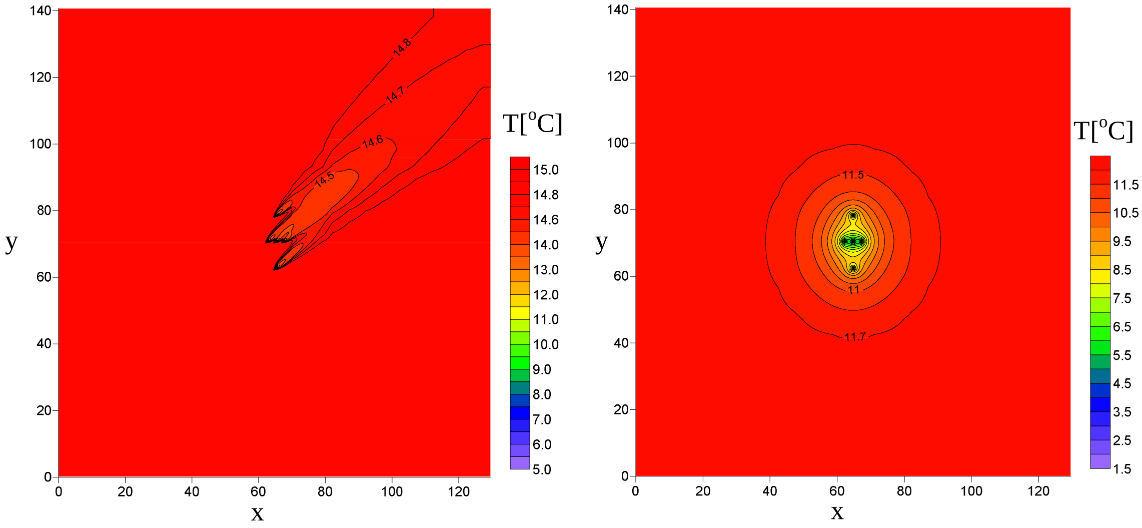

Figure 8: Temperature distributions around of boreholes (section at a depth of 9 m) in case of no underground flow (right) and with underground flow (left) after 2 years of operation

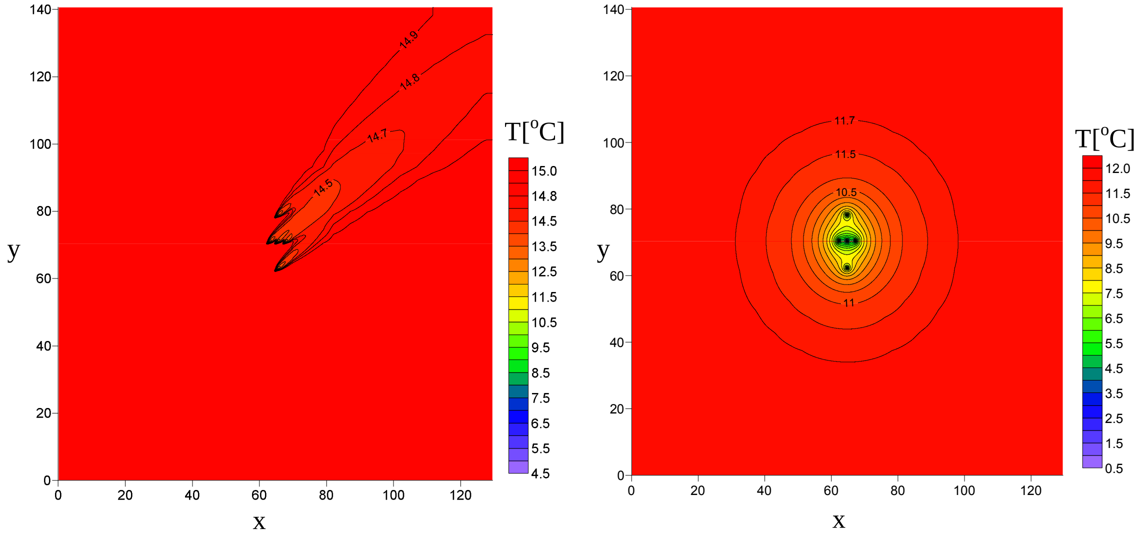

Figure 9: Temperature distributions around of boreholes (section at a depth of 9 m) in case of no underground flow (right) and with underground flow (left) after 4 years of operation

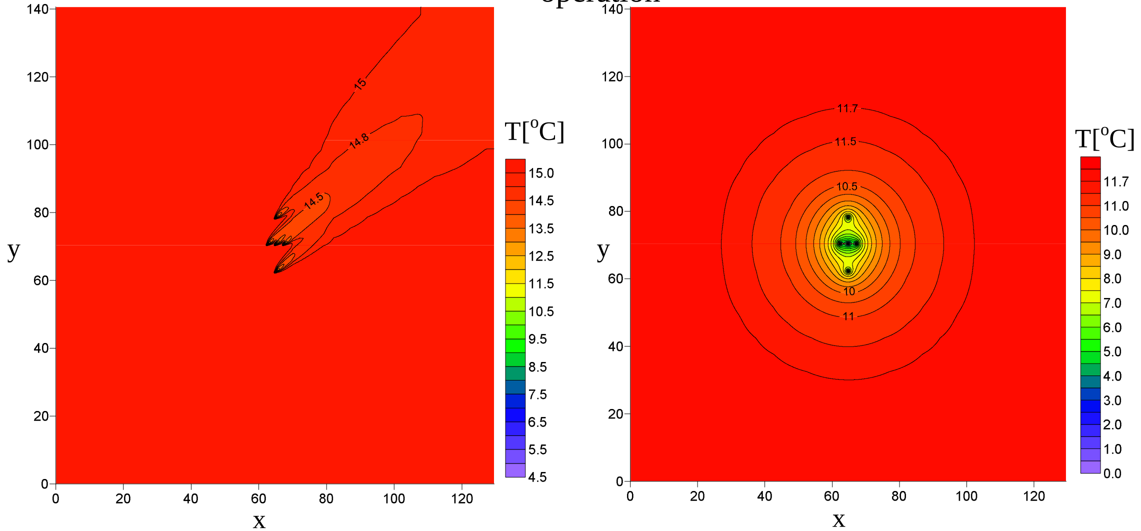

Figure 10: Temperature distributions around of boreholes (section at a depth of 9 m) in case of no underground flow (right) and with underground flow (left) after 6 years of operation

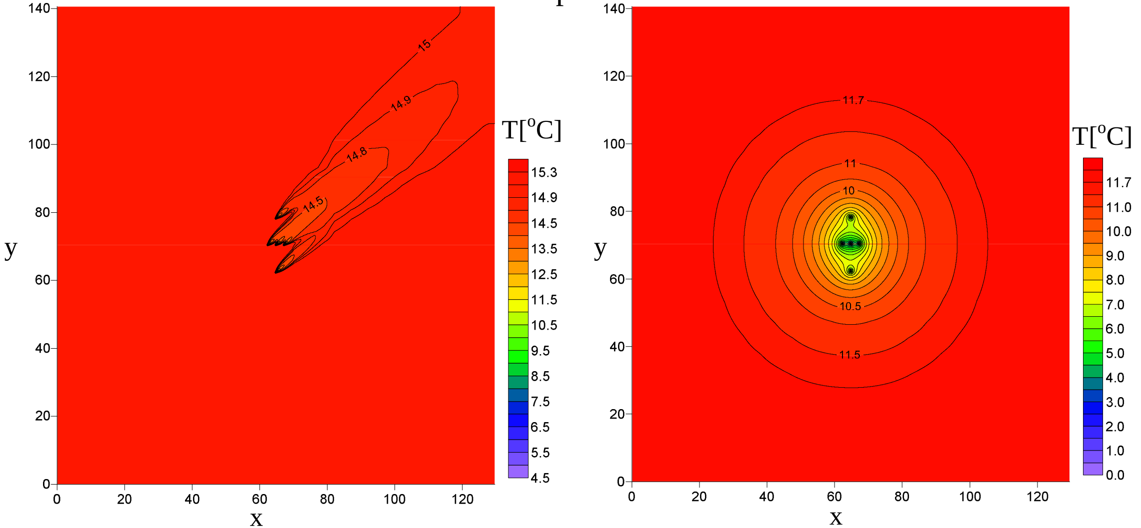

Figure 11: Temperature distributions around of boreholes (section at a depth of 9 m) in case of no underground flow (right) and with underground flow (left) after 8 years of operation

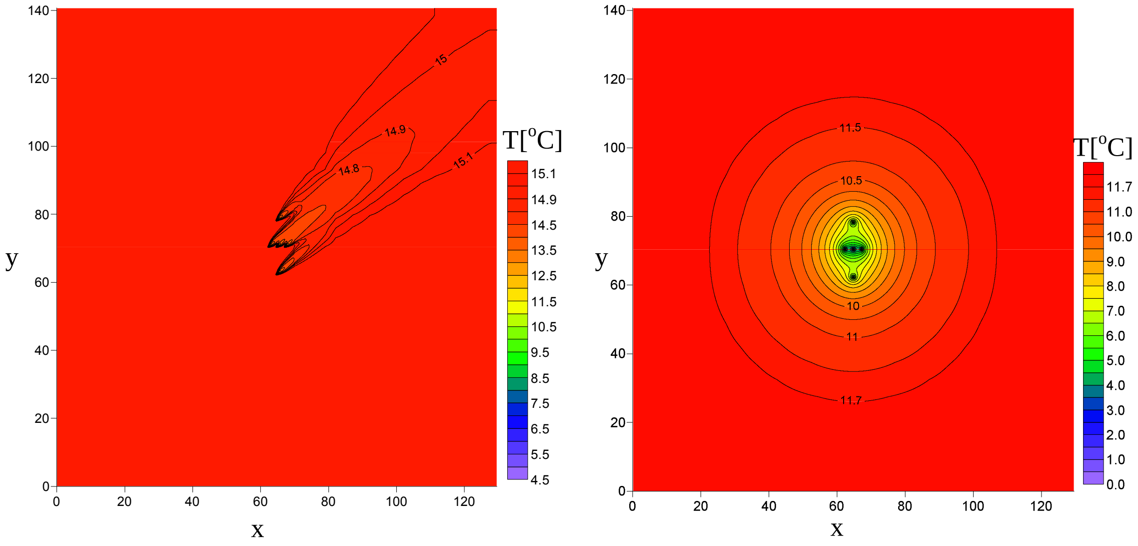

Figure 12: Temperature distributions around of boreholes (section at a depth of 9 m) in case of no underground flow (right) and with underground flow (left) after 10 years of operation

CONCLUSION

In the present paper numerical model has been developed to study heat transport in the geothermal system consist of five borehole heat exchangers and the surrounding soil. Focus was placed on the long-term temperature distribution in the soil containing underground water flow and understanding of its importance in the geothermal system.

Maximum thermal power or energy extracted from the soil depends on the type of soil formation. Formation with larger thermal conductivity and larger thermal diffusivity results in higher power and larger amount energy can be extracted without lost in heat pump efficiency. But in similar way as increase in soil conductivity works flow of water in hydrogeological layer results. It also results in increasing performance of BHE (Fig. 4 and 5). This effect is very strong and results in much slower decreasing in temperature of the soil around BHE. Here underground flow area directly cover only 14 % of computational tube and in many cases this effect can be more pronounces. This effect may be primary effect in soil regeneration after heating season. The underground water flow in occurring only in interval 3-15m and for soil with 30% saturation but effect for velocity higher than $6.3*10^{-7}$ m/s was already seen. Soil conductivity is important for long period but for soil regeneration this parameter is less important than the underground water flow.

In many cases phase change (freezing water) may play also important role and allow to transfer additional heat from the ground without lost in efficiency. This additionally increases conductivity of the soil but at the same time this stops underground water flow which as was shown is very welcome for performance and for regeneration of geothermal system and more important than just increase in conductivity.

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