Computer Assisted Methods in Engineering and Science, **20**: 227–235, 2013.

TWENTY YEARS OF THE CAMES

The analysis of long-term borehole heat exchanger system exploitation

Marek Jaszczur, Tomasz Śliwa
AGH University of Science and Technology
30 Mickiewicza Ave, 30059 Kraków, Poland
e-mail: marek.jaszczur@agh.edu.pl

The key issue in designing borehole heat exchangers (BHE) is the long-term performance of the ground source heat pump (GSHP) systems. The performance directly reflects economic profitability and depends on a large number of parameters including rock formation, the construction of the borehole heat exchangers, working parameters (circulation rates) and thermal load. The objective of the paper is to perform a realistic long-term (up to 10 years) analysis of the ground system to show possible degradation of efficiency over time. A mathematical model of the heat transfer in a borehole heat exchanger and the surrounding area has been constructed for parameters of the currently running experimental system. The long-term performance of the ground source heat pump system is evaluated.

Keywords: borehole heat exchangers, reservoir engineering, heat pumps systems, geoenergetics.

NOMENCLATURE

ρ, c, k – soil density, specific heat and heat conductivity,
ρ_c, c_c, k_c – cement density, specific heat and heat conductivity,
ρ_f, c_f, k_f – working fluid density, specific heat and heat conductivity,
ρ_t, c_t, k_t – tubes density, specific heat and heat conductivity,
q – working fluid flow rate,
T – underground system temperature (soil any material or working fluid),
T_{in} – temperature at the inlet to the ground heat exchangers' tube,
T_{out} – temperature at the outlet to the ground heat exchangers' tube,
U_x, U_y, U_z – underground flow velocity component.

1. INTRODUCTION

The efficiency of a single borehole heat exchanger (BHE) depends on a large number of parameters [1] including rock formation [2], construction of the borehole heat exchangers [5], heat pump model and also working parameters (circulation rates) [3] and the character of the thermal loads. In systems consisting of many borehole heat exchangers the problem is even more complex due to common interactions.

In Poland, a lot of exploited wells are liquidated after drilling (about a thousand closed deep drill-holes [2]). They could instead be used as a good heat source, providing many local environmental and economic advantages [4]. The use of these wells for district heating requires co-operation with heat pumps for the improvement of geothermal energy. The Podkarpacie region in the south-eastern part of Poland was the birthplace of the country's oil and gas industry. There are plenty of old wells, often they are over 100 years old. Following the depletion of their hydrocarbon resources, these wells could be either liquidated, which is expensive, or used as borehole heat exchangers, which may turn out to be profitable. The results of the numerical simulation and economic analysis show that borehole heat exchangers may have many advantages. Many analyses concerning several aspects of ground exchangers have been studied by Składzień *et al.* [6] and Hanuszkiewicz-Drapała [3]. Independent of the type and depth of BHE, the amount of heat that can be transferred from the soil to the heat pump system must be carefully analyzed. Otherwise, system efficiency will be seriously decreased. Degradation in performance may occur permanently and, after many years, total system efficiency will be much lower than when the system was new and the soil had its original temperature profile. Possible ground freezing can be so serious as to permanently damage outer tubes or change thermal contact (micro-space), which increases the thermal resistance between the borehole tubes and soil. The system will eventually end up with a far lower total efficiency than it initially had.

Hence, the objective of the paper is to perform realistic long-term (up to 10 years) analysis to show possible efficiency degradation over time. We constructed a mathematical model of the heat transfer in the borehole heat exchanger and surrounding area for parameters of the currently running experimental system presented in Fig. 1. Different cases taking into account the most important parameters, including power consumption and type of soil formation, are presented. A comparison of the numerical results with experimental results for TRT test performed at the AGH University test field is shown.

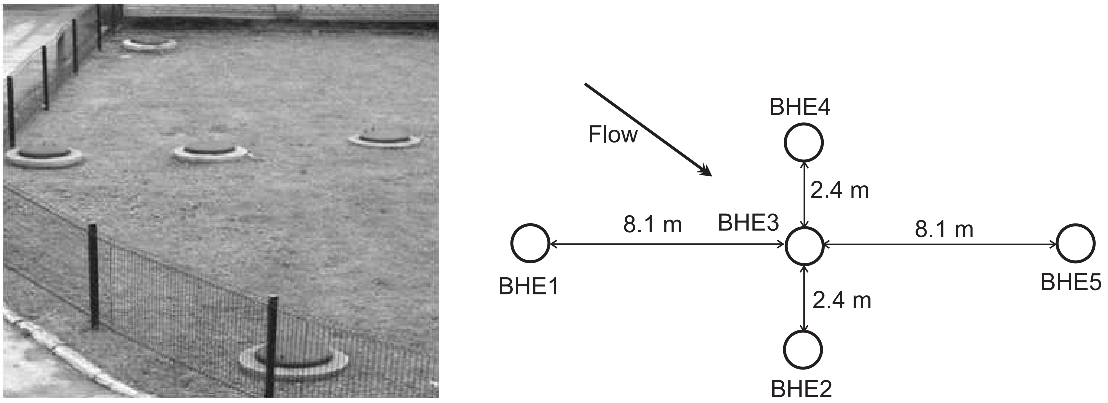

Fig. 1. An experimental test field at AGH University.

2. Numerical model

The governing energy equations for the three-dimensional unsteady heat transfer in the geothermal system are solved for the soil (domain 1) and in the borehole heat exchangers (domain 2) [2]. The governing energy balance equation for the three-dimensional unsteady heat transport in the soil takes the form:

$$\rho c \frac{\partial T}{\partial t} + \rho c \left(U_x \frac{\partial T}{\partial x} + U_y \frac{\partial T}{\partial y} + U_z \frac{\partial T}{\partial z} \right) = k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + s, \tag{1}$$

where ρ, c and k are the physical properties of the soil formation which are z direction (depth) dependent. The source term s allows other effects in the soil, for example natural heat sources and/or phase changes to be taken into consideration. To model heat transfer in solid materials (cement,wall tubes) a simplified version of Eq. (1) is used:

$$\rho_c c_c \frac{\partial T}{\partial t} = k_c \frac{\partial^2 T}{\partial x^2} + k_c \frac{\partial^2 T}{\partial y^2} + k_c \frac{\partial^2 T}{\partial z^2}, \tag{2}$$

where the physical properties of the cement used are replaced with the properties of other solid materials (for example tubes). Assuming there is no chemical reaction or phase change in the working fluid, the energy balance equation for the working fluid in heat exchangers, tubes can be described as

$$\rho_f c_f \frac{\partial T}{\partial t} + \rho_f c_f U_f \frac{\partial T}{\partial z} = k_f \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right), \tag{3}$$

where all the physical properties are now for the working fluid and U_f is the unified velocity inside the tube calculated from the flow rate and actual borehole heat exchangers, tube type. Using the mathematical model, the system temperatures which reflect the system performance dependence on the soil formation properties, heat exchanger type (coaxial, single U-tube and double U-tube – see Fig. 2 for reference) and total power are studied. The boundary conditions and initial condition associated with the thermal field are

for $z=0$ $\quad T = T_{air}(t)$ top surface,

for $z=L_z$ $\quad \dfrac{\partial T}{\partial z} = q_e$ bottom surface,

for $x = 0, L_x; y = 0, L_y$ $\quad \dfrac{\partial T}{\partial z} = 0$ other surface

on the working fluid interaction surface with the inner tubes wall the following boundary conditions are applied:

$$-k_f \frac{\partial T}{\partial n} = h_{fc} \left(T_f - T \right). \tag{4}$$

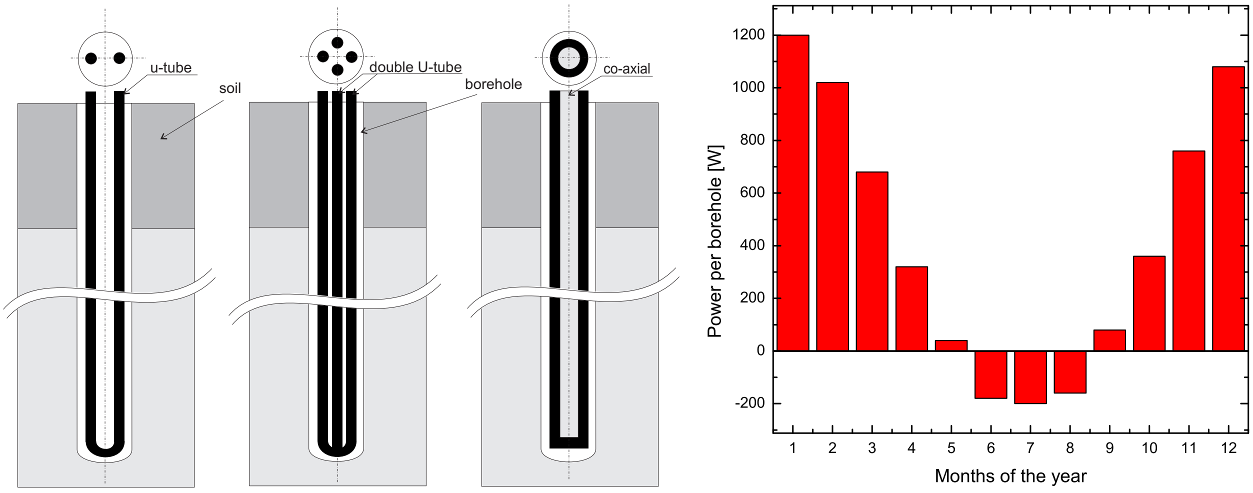

Fig. 2. Geometry of BHE (left) and power distribution over the year (right).

For the determination of the heat transfer coefficient h_{fc} for flow in a pipe depending on flow regimes the following correlations for the Nusselt number have been used:

$$Nu = 3.66 + \frac{0.065 Re Pr d_w / l}{1 + 0.04 \left(Re Pr d_w / l \right)^{2/3}} \qquad \text{for} \qquad Re < 2000, \tag{5}$$

$$Nu = 0.00069 Re^{1.24} Pr^{1/2} \qquad \text{for} \qquad 2000 < Re < 10000, \tag{6}$$

where Pr is the Prandtl number and Re is the Reynolds number, d_w is tube inner diameter and l is the tube length. The temperature of the top surface ($z = 0$) varied over time according to realistic weather's air temperature $T_{air}(t)$. The numerical model of the top surface including all important effects (Sun's radiation, Earth's radiation, natural and forced convection or snow all based on realistic available weather measurement) was also considered and implemented into the developed numerical code. But the conclusion from this complex and very time-consuming simulation was clear. Assuming air temperature on the top surface or modelling with complex "environmental model" including most of the effects results in a very similar temperature variance in the soil. In the present simulation, weather conditions collected for 1996 at Kraków peripheries area are used and repeated 10 times (in similar way as a thermal power is repeated). The heat exchanger's tubes ($L = 78$ m) were initially filled with water with the thermal equilibrium of the soil formation. The working fluid was a 30% water solution of glycol and the simulation time was set at 10 years. The variance of the thermal power per borehole, with a distribution typical for Poland, is presented in Fig. 2. During the heating season, heat is transferred from the soil (positive) while in the summer period a small amount of heat is transferred to the soil. We assume the total energy consumption (from the soil) to be 100 kWh/(year·m^2), a typical value for a modern, 200 m^2 home. At initial time t the desired power was applied and every year had an identical thermal power distribution.

The cold fluid (in winter) with temperature T_{in} is injected down the BHE (inner tube in coaxial heat exchangers, U-tube, two U-tubes) while the fluid with higher outlet temperature T_{out} is left out. The space between the tube and soil is cemented along its full length. For the condition presented here the soil is considered to be one- or two-phase porous material in which underground water flow at intervals may occur from 3 to 15 m under the surface. The details about the mathematical description and numerical procedure can be found in [2]. The physical parameters related to the geometry are presented in Fig. 2 and the properties of the working fluid are listed in Table 1 and 2. The working fluid properties in the heat exchangers depend on the local

Table 1. Soil average thermal properties.

Soil properties		
Formation type	Thermal conductivity	Heat capacity
	W/(m·K)	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

Table 2. Fluid properties and dimensions of BHE1, 2–4 and 5 tubes.

		Parameter	Value
Construction of BHE	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/(m·K)
	c_f	Fluid specific heat	3906 J/(kg·K)
	ν	Fluid viscosity	$4.16 \cdot 10^{-6}$ 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

temperature but the difference in properties is usually very small. As shown by Hanuszkiewicz-Drapała [3] temperature effect on fluid flow can be typically neglected. The soil mean (weight average) properties, which may be found in Table 1, are assumed to be constant except for those cases where water froze in the soil (soil latent heat 100 kJ/K) – there was a water fraction of 30% – and the properties of ice were proportionally introduced ($\rho = 916.2$ kg/m^3, $c = 2050.0$ J/(kg·K), $k = 2.22$ W/(m·K)). The following material properties have been set for the tubes: $\rho_t = 912$ kg/m^3, $c_t = 1200$ J/(kg·K), $k_t = 0.45$ W/(m·K). The space between the outer tube and soil has been fully filled with cement of a density of $\rho_c = 2180$ kg/m^3, specific heat $c_c = 1130$ J/(kg·K) and a conductivity of $k_c = 1.2$ W/(m·K) (2.0 for BHE3, 1.8 for BHE4). Parallel numerical algorithm written in Fortran 90 based on a control volume method of Cartesian grid was developed to solve model equations (1)–(6). The Adams-Bashforth method was used to approximate the unsteady terms and either central difference CDS or a hybrid method was used for the convectiver/diffusive terms. To solve the unsteady problem accurately and for long period of time, time step was not constant during the computations but varied in a range from $\Delta t_{\min} = 60$ up to $\Delta t_{\max} = 7200$ s so that it would be optimal at any given time. The grid size used here was $200 \times 200 \times 100$ control volumes ($N_x \cdot N_y \cdot N_z$) for the domain of size $40 \times 25 \times 100$ m. The borehole heat exchange and near borehole area (up to $50D$) was a locally much finer grid (up to 50 times) to accurately approximate the heat exchangers. This was accomplished using the local grid refinement technique with iterative convergence procedure. In order to model phase change problem (water freezing in the soil) the apparent heat capacity method was implemented into the numerical code. Validation was performed for several cases. For the test case with unsteady infinite linear source, the relative temperatures compared to analytical solutions at the time 24 h after initial uniform state differed for the distanced $r = 0.1$-5 m from the center line of the pipe less than 0.1%. The results of the experimental validation are presented in the next section.

3. RESULTS

The mathematical model and numerical procedures described in the previous section were used to perform the parametric study of the influence of the soil formation properties and power consumption on outlet temperature T_{out}. Inlet temperature T_{in} was calculated as a result of the desired power at any time (positive power means that the heat is transported from the soil to the heat pump while negative power means it is transported in the opposite direction) and the outlet temperature T_{out} is a result of the inlet temperature and heat exchange with the soil. The boundary conditions on the side walls of the domain are adiabatic; the top surface has a realistic weather condition and at the bottom Earth natural heat flux was set $q_e = 100$ mW/m^2 at the bottom. The initial temperature T_{init} was obtained from the measurement of the soil and it is presented in Fig. 3. At initial time $t = 0$ the pump starts working with a flow rate of 20.0 dm^3/min. The simulation time was set at $t = 10$ years.

3.1. Validation

Figure 3 presents comparisons between experimental data and numerical simulation for a thermal response test (TRT) on the BHE4 at the Drilling and Geoengineering Department's Geoenergetics Laboratory of Drilling at AGH University of Science and Technology in Kraków. Given a large number of important parameters, which are not easy to determine, the comparison is very good.

3.2. Long-term analysis

Three types of soil formation were selected to study the effect of the varying thermal properties of the soil. Figure 4 presents a contour of soil temperature in a horizontal cross-section ($z = 9$ m

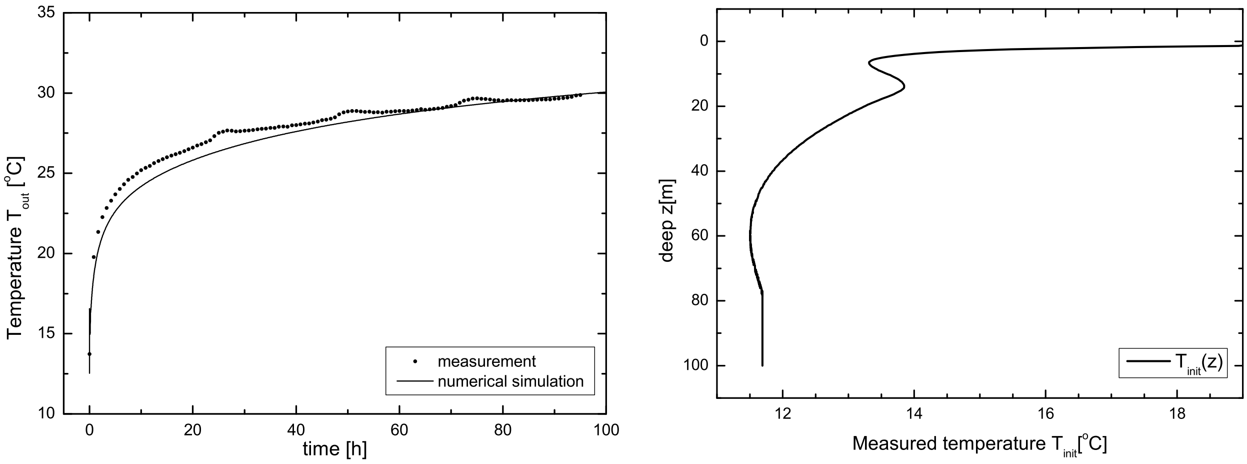

Fig. 3. TRT of BHE4 vs numerical data (left) and initial temperature profile (right).

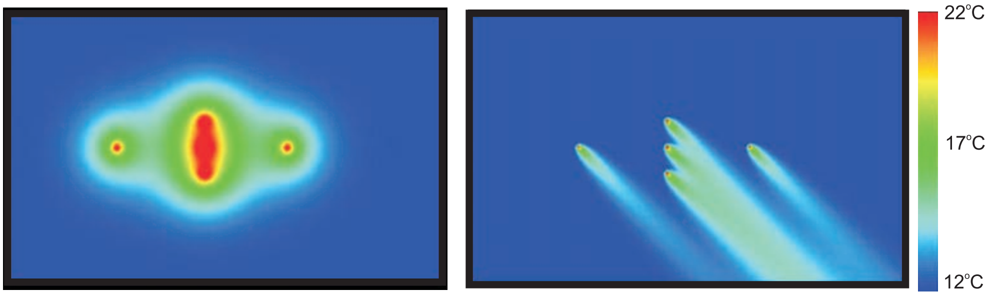

Fig. 4. Temperature around boreholes without (left) and with (right) underground water flow.

below the top surface) containing five borehole heat exchangers and soil. Results show temperature distribution during heating (TRT) test when the heat is transferred to the soil. Similar situation occurs after summer time when the air in house is cooled. This significant influence of underground flow on temperature field as well thermal interactions between each heat exchanger can be observed. When the BHEs are located to close as BHE(2–4) the strong interaction between them can be observed. This undesired interaction become less important when the flow occurs.

The results presented in Fig. 5 show that borehole heat exchangers are influenced both by geological conditions and the heat exchanger type used. Fluctuation of the outlet temperature is larger for low conductivity soil and after 10 seasons the simulation completes with a relatively low minimum temperature of around −5°C. Outlet temperatures presented on the left plots in Figs. 4–7 are fitted to the exponential decay function:

$$T_{out}(t) = T_o + A\cdot e^{(t-t_o)/B}, \tag{7}$$

where T_o, t_o, A and B are fitting constants Fitted temperatures can be related to the long term working fluid average temperature outgoing from heat exchangers borehole and are presented on the right side of the figures. It can be seen that average temperature decreases over time. The largest and fastest decrease was observed for soil I while the smallest was for soil II with underground flow. Figure 5 (the bottom plots) presents the outlet temperature for all five types of BHE and for soil II. The maximum and minimum outlet temperatures T_{out} depend on the heat exchanger type as well as the location in the field; these temperatures differ between BHE around 1–2°C. For all the constructions the outlet temperature results in a long-term temperature decrease that is independent of construction. It can be seen that BHE5, which consists of double U-tubes, performs much better than other types and shows a much slower temperature decrease.

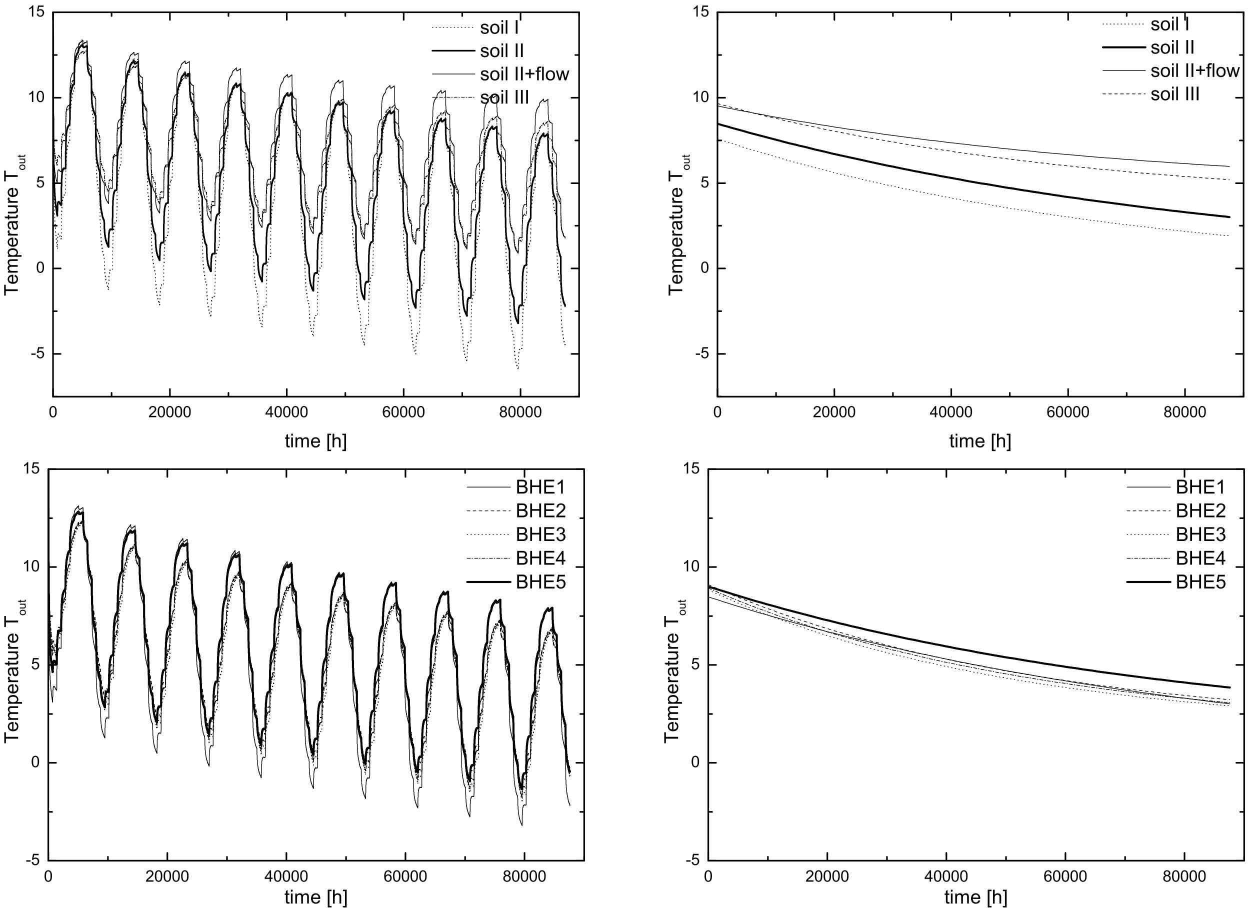

Fig. 5. Outlet temperature T_{out} vs time (left) and exponential decay fitting (right).

Figure 6 shows the influence of power amplification on the outlet temperature and the exponential decay fitting temperature. For this test, the power distributions have been multiplied either by a factor of two (power*2) or four (power*3). The effect of the additional power is considerable. Increasing soil conductivity from soil II to soil III can slow the decrease of the average outlet temperature but this effect is weaker than that of the underground water flow. The underground flow was set according to experimental underground flow measurement at AGH University test station. Flow was detected to occur at intervals from 3 to 15 m under the top surface and at an internal velocity of $U_x = U_y = 0.218 \cdot 10^{-4}$ m/s, $U_z = 0$. The effect of underground flow is very strong and results in a much slower decrease in the average temperature. If the power is four times higher than the reference power then even for the case of underground water flow outlet temperature T_{out} is very low. The outlet temperature in the winter period (T_{out} below $-15°$C) is comparable with the lowest temperature of the air but in the case of the borehole heat exchangers cannot be accepted because of possible damage to the underground construction by deep freezing water in the soil and attendent increasing stresses that occur in the soil. All previous results do not take into account phase change nor latent heat and in Fig. 7 the influence of this two effects is shown. In cases when the soil containing the water (30%) freezes, two major effects play an important role. The first is the additional heat due to phase change, which is large for the large area influenced by BHE, and the second effect is due to the increasing conductivity of the soil. For the basic power (power*1) the effect of phase change is weak-even after 10 years no difference can be seen. However, for the two times higher power (power*2) the effect is large. The minimum temperature is 5°C higher in comparison to the cases without phase changes. This is a very positive effect which will increase the heat pump system efficiency, but the maximum temperature is also larger and will, by contrast, decrease heat pump performance in the summer.

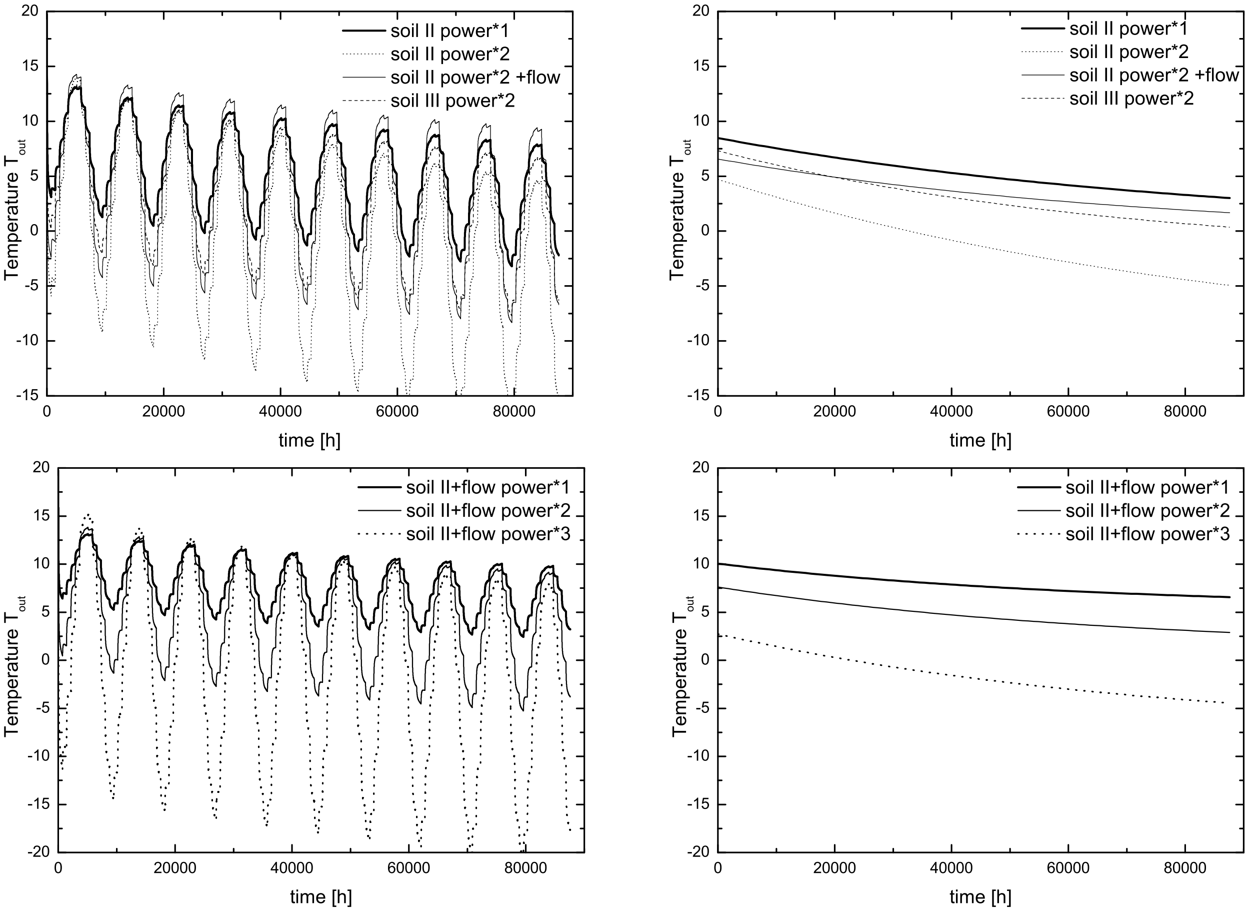

Fig. 6. Outlet temperature T_{out} vs time (left) and exponential decay fitting (right) for different power magnitudes and soil types and for construction BHE5.

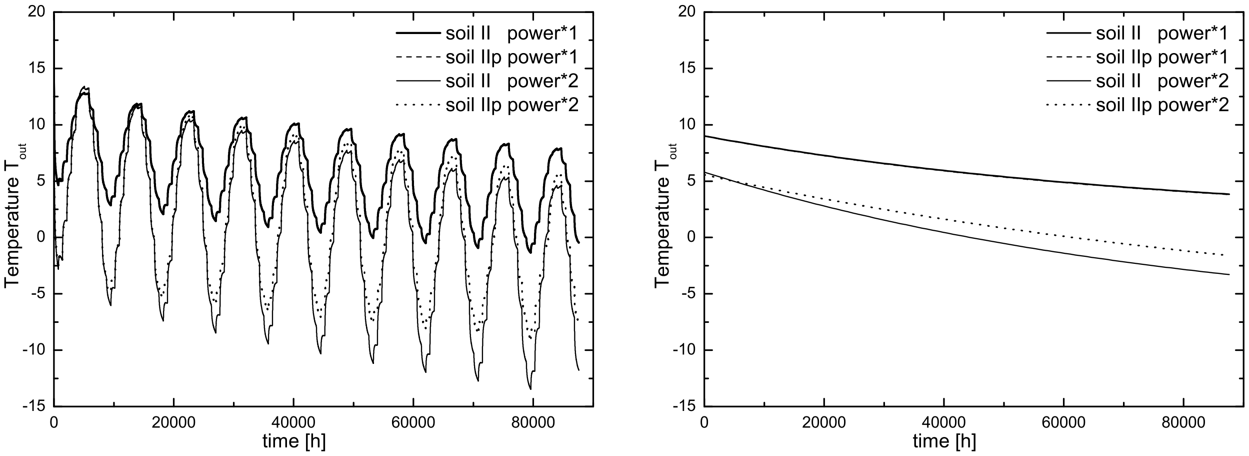

Fig. 7. Outlet temperature T_{out} vs time (left) and exponential decay fitting (right) for different power magnitude and soil type II including phase change (soil IIp) effect (for BHE5).

4. CONCLUSIONS

In presented paper, the focus has been placed on the long-term analyses of the ground heat exchangers which are main parts of the ground source heat pump (GSHP) systems. Temperature delivery by the ground system – the outlet temperature from the heat exchangers T_{out} directly reflects the systems' performance as well as their profitability and depends on a large number of parameters. Numerical computations performed for realistic conditions (real soil parameters, real weather condition and variable weather dependent power consumption) show that after a few seasons the mean outlet temperature T_{out} decreases, which will directly affect the efficiency of the heat pump system and the coefficient of performance (COP). The effect of additional power consumption and the difference in soil properties have been analyzed together with the underground water flow and phase change. Based on the results of numerical calculations, the following conclusions can be drawn. Thermal power or energy extracted from the soil is sensitive to the type of soil formation. Formation with larger thermal conductivity and larger thermal diffusivity results in higher power and greater energy extraction. Water flow in the hydro-geological layer also results in better BHE efficiency (Figs. 5 and 6). This effect is very strong and leads to the average temperature to decrease much more slowly. In present paper, according to experimental measurement the underground flow occurs at intervals 3–15 m below the surface and directly influences only 15% of the length of the heat exchanger tube. In many cases this interval could be larger. After 10 years the average COP base on the reversed Carnot cycle for low temperature domestic heating system ($T_h = 40°\mathrm{C}$) will be COP = 8.46 (from Fig. 5 for no flow $T_{out} = 3°\mathrm{C}$) versus COP = 9.20 ($T_{out} = 3°\mathrm{C}$) for underground water flow considered here. For real heat pump COP will be smaller but the difference may remain the same. For example, for the modern heat pump available in the market COP for above conditions will be 4.29 and 4.65 and the increase is almost 8% and which is similar to the Carnot efficiency increase. This 8% is roughly the amount necessary to prepare hot water for domestic use. Underground water flow may be the primary effect in soil regeneration after the heating season. The effect of increase in soil conductivity after phase change on this phenomenon is important but it is weaker than the underground water flow. The soil obtains initial temperature faster (regeneration) with the presence of water flow than without the flow, even for soil with slightly higher conductivity. In many cases, due to temperatures lower than 0°C, the latent heat of frozen water may be important. As can be seen, this effect may be important for large power. Typically such a high power should not occur for a long period but may be necessary when the air temperature is very low. Phase change effect may then play a primary role and allow additional heat to be transferred from the soil without a loss in efficiency. In all the cases considered, the average temperature decreases over time. In some cases, the average temperature after 10 years is only less than 1°C lower than the average temperature after the first year. In other cases the average temperature decreases by as much as 1°C per year, which results in a large efficiency decrease in time. On the other hand, if the system is properly designed and underground water flow occurs even to a small extent, outlet temperature decrease is slow and thus degradation in efficiency is low.

ACKNOWLEDGEMENTS

A part of the present work was supported by the Grant AGH No. 11.11.210.198

REFERENCES

[1] A. Chiasson. *Advances in modeling of ground-source heat pump system.* University of Windsor, Canada, 1989.
[2] A. Gonet, T. Sliwa, S. Stryczek, A. Sapinska-Sliwa, M. Jaszczur, L. Pajak, A. Zlotkowski. *Methodology for the identification of potential heat of the rock mass along with technology implementation and operation of the borehole heat exchangers.* Wydawnictwa AGH, Krakow, 2011.
[3] M. Hanuszkiewicz-Drapała. Modeling of thermal phenomena in ground heat exchangers of heat pumps taking into account hydraulic resistances. *Modelling in Engineering*, **38**: 57–68, 2009 (in Polish).
[4] K. Morita. One Possible Way to Utilize Abandoned Deep Wells – the Application of the DCHE. *International Scientific Conference – Geothermal Energy in Underground Mines*, 129–148, 2001.
[5] M.J. O'Sullivan, K. Pruess, M. Lippmann. State of the art of geothermal reservoir simulation. *Geothermics*, **30**: 395–429, 2001.
[6] J. Składzień, M. Hanuszkiewicz-Drapała, A. Fic. Thermal Analysis of Vertical Ground Exchangers of Heat Pumps. *Heat Transfer Engineering*, **27**: 2–13, 2006.