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NUMERICAL MODEL OF BOREHOLE HEAT EXCHANGER IN ANSYS CFX SOFTWARE

NUMERYCZNY MODEL OTWOROWEGO WYMIENNIKA CIEPŁA W PAKIECIE ANSYS CFX

The paper presents the results of numerical simulation of thermal response test (TRT) and the results of the experiment of TRT in Johan Paul the second Centre "*Have No Fear!*" in Cracow. The aim of the study is to determine and compare the values of effective thermal conductivity of rocks obtained in TRT experiment with the results obtained from the numerical simulation of TRT. The results are shown as graphs of temperature variation in the time on inlet and outlet of the borehole heat exchanger (BHE) and as drawings of thermal distribution. Borehole heat exchanger is constructed of a single u-tube at a depth of 180 m. In the numerical simulation of TRT was included geological profile of the rock mass and the associated changes in thermal properties of rocks. Temperature dependence of liquid viscosity were also adopted. Groundwater flow has been neglected. Presented mathematical model based on energy balance equation, Navier–Stokes equation and flow continuity equation was solved using the finite volume method. To numerical calculation was used ANSYS CFX software.

Keywords: Borehole heat exchanger (BHE), thermal response test (TRT), CFD, numerical simulation

W pracy przedstawiono wyniki numerycznej symulacji testu reakcji termicznej górotworu (TRT) oraz wyniki z przeprowadzonych badań polowych badawczego wymiennika otworowego w budowanym Centrum Jana Pawła II „Nie lękajcie się" w Krakowie-Łagiewnikach. Celem pracy jest określenie oraz porównanie wartości efektywnej przewodności cieplnej skał otrzymanej w badaniach polowych z wynikami otrzymanymi z numerycznej symulacji testu TRT. Wyniki przedstawiono w postaci wykresów zmian temperatury nośnika ciepła w czasie na zasilaniu i powrocie z otworowego wymiennika ciepła oraz w formie rysunków przedstawiających rozkłady pól temperatury. Otworowy wymiennik ciepła zbudowany jest z pojedynczej u-rurki o głębokości 180 m. W numerycznej symulacji testu uwzględniono profil litologiczny górotworu oraz związane z tym zmiany właściwości termicznych skał. Uwzględniono również zmiany lepkości czynnika grzewczego od temperatury. Nie uwzględniono natomiast przepływu

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wód podziemnych. Przedstawiony model matematyczny oparty na równaniach bilansu energii, równaniach Naviera-Stoksa oraz równaniach ciągłości przepływu rozwiązano z wykorzystaniem metody objętości skończonych. Obliczenia numeryczne przeprowadzono w środowisku Ansys CFX.

Słowa kluczowe: Pionowy otworowy wymiennik ciepła, test reakcji termicznej TRT, CFD, symulacja numeryczna

1. Introduction

The subjects of energy saving, sustained development and reduction of CO_2 emission have recently resulted in the implementation of more efficient technologies of energy production from renewable sources (Solik-Heliasz et al., 2009; Staśko et al., 2006). One of such technologies are heat pumps installed with borehole heat exchangers.

The first theoretical works on borehole heat exchangers appeared in the 1940's and 1950's (Ingersoll et al., 1956) whereas the most important works on BHE were written in the 1980's and 1990's (Eskilson, 1987; Hart et al., 1986; Kavanaugh et al., 1991; Kohl, 1992; Kujawa et al., 1998; Pruess, 1999; Pająk, 1999). A number of analyses and investigations of borehole heat exchangers were performed also in Poland (Śliwa, 2002, 2004).

The heating/conditioning system in the John Paul the Second Centre "*Have No Fear!*" in Cracow will be based on borehole heat exchangers and heat storage at rock mass. The tests were performed in two special experimental boreholes (Gonet & Śliwa, 2010a); one with a single U-tube to 180 m and the other one with a double U-tube to 162 m of depth. The TRT tests were carried out in experimental boreholes (Gonet & Śliwa, 2010b). The investigations and analyses were aimed at selecting a proper design of 60 borehole heat exchangers cooperating with electricity-fed heat pump supplied from the cogeneration aggregate.

The values of efficient thermal conductivity of rocks obtained in field experiments and from numerical TRT simulation were compared in the paper. The lithological profile of the rock mass was presented in Table 1.

The most important drilling data were listed in Table 2. Detailed parameters of borehole heat exchanger P-1 (single U-tube) were as below:

- Diameter of borehole D_o (diameter of drilling tool) D_o = 159 mm (to depth of 36 m b.s.), D_o = 153 mm (in interval 36 – 180 m),
- Depth of borehole H = 180 m,
- Depth at which BHE tubes were tripped H_w = 180 m,
- Distance between pipes axes, k, assumed k = 70 mm,
- Type of material used as grout – bentonite suspension Hekoterm, thermal conductivity λ = 2.0 $Wm^{-1}K^{-1}$,
- Outer diameter of pipes d_z = 40 mm,
- Thickness of pipe wall b = 3.7 mm,
- Material of pipes – polyethylene, λ = 0.42 $Wm^{-1}K^{-1}$.

TABLE 1

Lithology profile and rock properties for borehole P-1 (single U-tube)

No.	Lithology	Thermal conductivity, λ, W m^{-1}K^{-1}	Specific heat, c_p, J kg^{-1}K^{-1}	Density, ρ kg m^{-3}	Thermal diffusivity, a m^2 s^{-1}
1	limestone sediment	2.2	867.9	2650	9.56e-7
2	dusty clays, warp, sand, peat	1.6	1280	1875	6.66e-7
3	dark grey mudstones	2.2	978.7	2350	9.56e-7
4	claystone and mudstones with intercalations equal grain sandstone	2.2	884.6	2600	9.56e-7
5	light grey limestones	2.4	867.9	2650	1.04e-6
weighted average:		2.2	932.27	2473.06	9.55e-7

TABLE 2

Most important data of the borehole P-1 with a single U-tube (Z. Bigaj borehole P-1 card)

Site	Kraków-Łagiewniki, geographical coordinates x = 50°0'54.07", y = 19°56'15.62", z = +232
Beginning of works	25 May 2010
Completion of works	27 May 2010
System and drilling technique	rotary, percussion-rotary

2. Object of research

The research was focused on a vertical borehole heat exchanger (single U-tube). The processes taking place within the borehole (fig. 1), and also in the neighbourhood of the borehole heat exchangers, i.e. in the rock mass, which is a heat reservoir of definite thermal capacity, were

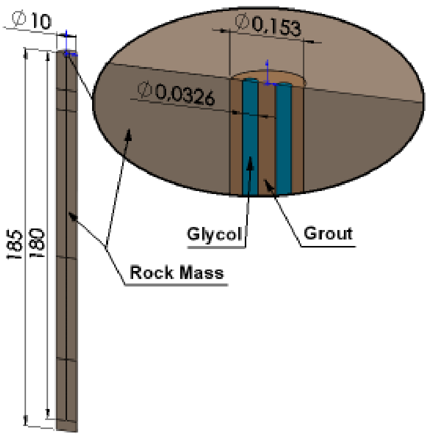

Fig. 1. Object of research – model of heat exchanger, a single U-tube

simulated. The model was performed with the use of software SolidWorks, and then imported to environment ANSYS CFX. The analysed zone of the borehole heat exchanger with a single U-tube was symmetrical, therefore could be simplified and only half of it analysed as presented in fig. 1.

3. Description of physics of the phenomenon

Heat transport in the closest vicinity of a borehole heat exchanger is described by a function of spatial coordinates and time. This issue is also connected with the flow of fluid. This interrelation involves heat transfer through convection from fluid to the U-tube, and then through conduction to grout and rock mass. It was assumed that the convection heat exchange in the rock mass can be neglected (lack of water-bearing layer with water filtration). This assumption can be introduced for low-permeability rocks. In this case the heat transport in the rocks mass was described with a differential equation of unsteady heat conduction, i.e. Fourier–Kirchhoff equation:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)=c_g \rho_g \frac{\partial T}{\partial t} \tag{1}$$

where:

$T = T(x,y,z,t)$ — temperature, K,
c_g — specific heat of rocks, $J \cdot kg^{-1} \cdot K^{-1}$,
ρ_g — density of rocks, $kg \cdot m^{-3}$,
$\lambda_{x,y,z} = \lambda_g$ — thermal conductivity of rocks, $W \cdot m^{-1} \cdot K^{-1}$.

To determine the velocity, thermal and pressure field, the flow should be described with mathematical equations, e.g. in a rectangular coordinate system x, y, z. Five unknowns are in those equations, i.e.:

– three components of velocity: $v_x(x,y,z,t)$, $v_y(x,y,z,t)$, $v_z(x,y,z,t)$,
– temperature $T(x,y,z,t)$,
– pressure $p(x,y,z,t)$.

Therefore, for describing the flow of fluid in a borehole heat exchanger we need five equations composed of:

– equation of real fluid motion, known as Navier-Stokes equations,
– equation of fluid flow continuity,
– equation of heat exchange for fluid flow.

The following assumptions and simplifications were taken for the analyzed case of heat carrier flow in a borehole heat exchanger:

– incompressible fluid, therefore, $\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0$
– Newtonian fluid, and its thermo-physical properties (conductivity, specific heat, density) are constant and no chemical reactions or physical transformations take place.

For thus defined fluid we get the following equations:

- Navier–Stokes equation:

$$\rho\cdot\left(\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2}\right)+\rho g_x$$

$$\rho\cdot\left(\frac{\partial v_y}{\partial t}+v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_y}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v_y}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_y}{\partial z^2}\right)+\rho g_y \qquad (2)$$

$$\rho\cdot\left(\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)+\rho g_z$$

- Equation of continuity of flow:

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}(\rho v_x)+\frac{\partial}{\partial y}(\rho v_y)+\frac{\partial}{\partial z}(\rho v_z)=0 \qquad (3)$$

- Equation of heat exchange for fluid flow:

$$\frac{\partial T}{\partial t}+v_x\frac{\partial T}{\partial x}+v_y\frac{\partial T}{\partial y}+v_z\frac{\partial T}{\partial z}=\frac{\lambda_w}{\rho_w\cdot c_w}\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}+\frac{\partial^2 T}{\partial^2 z}\right) \qquad (4)$$

where:

v_x, v_y, v_z — components of flow velocity vector, $\mathrm{m\cdot s^{-1}}$,
$T = T(x, y, z, t)$ — temperature, K,
ρ_w — density of heat carrier, $\mathrm{kg\cdot m^{-3}}$,
$\mu = \mu(T)$ — dynamic viscosity of heat carrier, $\mathrm{Pa\cdot s}$,
c_w — specific heat of heat carrier, $\mathrm{J\cdot kg^{-1}\cdot K^{-1}}$,
$g_{x,y,z}$ — acceleration of gravity, $\mathrm{m\cdot s^{-2}}$,
λ_w — thermal conductivity of heat carrier, $\mathrm{W\cdot m^{-1}\cdot K^{-1}}$.

Solving above equations requires assuming initial and boundary conditions. It was assumed that the initial condition was connected with the influence of undisturbed environment in the rock mass. The rock temperature increases with depth owing to the influence of geothermal heat from inside of the Earth, in line with the geothermal gradient. The increase of temperature is congruent with fig. 6, which has been described with equation:

$$T(x,y,z,t)=T_a+G\cdot(y-h) \qquad (5)$$

where:

T_a — assumed temperature at a depth of 0 m, 55 m and 115 m, respectively, K,
G — geothermal gradient, $\mathrm{K\cdot m^{-1}}$,
h — depth, from which the temperature can be described as a linear function (depth of periodic penetration of heat to the rock mass), 0 m, 55 m, 115 m, respectively.

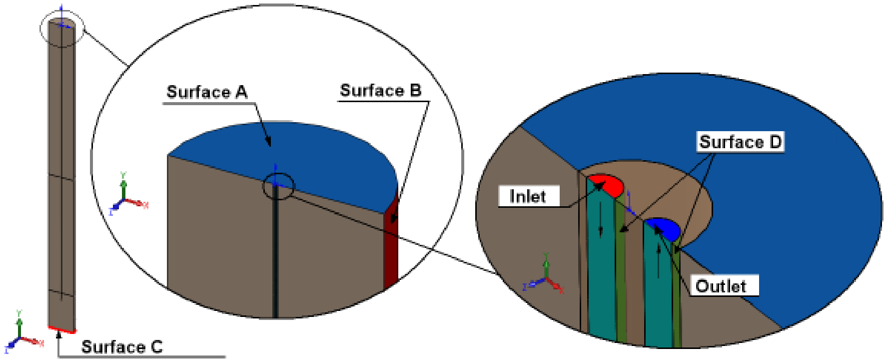

Fig. 2. Description of surface for initial and boundary conditions

There was assumed an initial condition quantitatively describing the increase of rock temperature, according to the formula:

$$
\begin{aligned}
&T(x,y,z,t) = -0{,}0046 \cdot y + 284{,}25 \quad \text{for} \;\; t = 0 \;\; \text{and} \;\; y \in \langle 0{,}55\, m \rangle \\
&T(x,y,z,t) = -0{,}0326 \cdot y + 282{,}7 \quad \text{for} \;\; t = 0 \;\; \text{and} \;\; y \in \langle 55{,}115\, m \rangle \\
&T(x,y,z,t) = -0{,}0206 \cdot y + 284{,}081 \quad \text{for} \;\; t = 0 \;\; \text{and} \;\; y \in \langle 115{,}180\, m \rangle
\end{aligned}
\tag{6}
$$

For the surface (A) and (B) the Dirichlet boundary condition was assumed, which has been presented in fig. 2 and described by:

$$
\begin{aligned}
&T(x,y,z,t)|_{A,B} = -0{,}0046 \cdot y + 284{,}25 \;\; \text{for} \; t \in \langle 0{,}100\, h \rangle \;\; \text{and} \;\; y \in \langle 0{,}55\, m \rangle \\
&T(x,y,z,t)|_{A,B} = -0{,}0326 \cdot y + 282{,}7 \;\; \text{for} \; t \in \langle 0{,}100\, h \rangle \;\; \text{and} \;\; y \in \langle 55{,}115\, m \rangle \\
&T(x,y,z,t)|_{A,B} = -0{,}0206 \cdot y + 284{,}081 \;\; \text{for} \; t \in \langle 0{,}100\, h \rangle \;\; \text{and} \;\; y \in \langle 115{,}180\, m \rangle
\end{aligned}
\tag{7}
$$

For the surface (C) the assumed geothermal heat flow rate was $q_g = 0.06 \text{ W} \cdot \text{m}^{-2}$. The velocity of heat carrier at the surface (D) of the analyzed model of U-tube equaled to zero, therefore, $v_x|_D = 0$, $v_y|_D = 0$, $v_z|_D = 0$. The defined mass flow at the outlet to the borehole heat exchanger equaled to $\dot{m}|_{inlet} = 0{,}3473 \text{ kg} \cdot \text{s}^{-1}$.

The assumed temperature at the inlet to the borehole heat exchanger U-tube was equal to the temperature at the inlet of the U-tube during the TRT (fig. 8). The analysis covered 75 hours of operation of the borehole heat exchanger. The knowledge of the lithological profile was necessary for the correct determining of thermophysical properties of rocks mass. It was assumed on the basis of table 1 that the analyzed area consisted of five layers with literature-based properties (Gonet, 2011).

The assumed values of specific thermophysical constants of a 33% propylene glycol solution are as follows:

– thermal conductivity $\lambda_w = 0.45$ W m^{-1} K^{-1},
– specific heat $c_w = 3725$ J kg^{-1} K^{-1},
– density $\rho_w = 1042$ kg m^{-3},
– dynamic viscosity of heat carrier $\mu(T)$, after fig. 3.

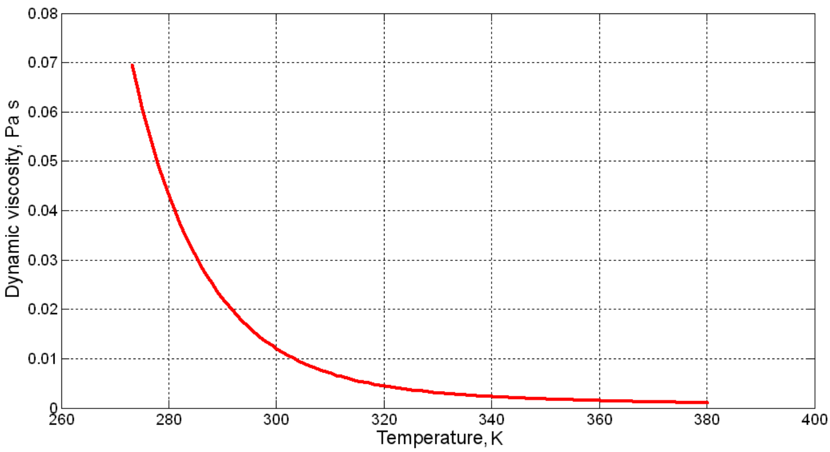

Fig. 3. Dynamic viscosity of 33% propylene glycol, Pa · s (Chem Group, 2011)

The assumed thermo-physical constants of the grout were the following:

– conductivity $\lambda = 2$ W m^{-1} K^{-1},
– specific heat $c = 1130$ J kg^{-1} K^{-1},
– density $\rho = 2000$ kg m^{-3}.

4. Results of field measurements

Temperature profiling in borehole P-2 (double U-tube) was performed on 25 June 2010. The thermal stabilization period was given in table 3.

TABLE 3

Borehole thermal stabilization period

Completion of all works in boreholes	29 May 2010
TRT period	24 June – 4 July 2010
thermal stabilization period after performing a borehole heat exchanger	25 days (required min. 14 days)

The results were graphically represented in fig. 4. Fig. 5 illustrates a distribution of temperatures in the near-surface zone of the rock mass, characteristic of the season the year. In interval 10-40 m the temperature has a constant value, which most probably was a result of infiltration of rain waters (big precipitations in May). The variability of geothermal gradient was illustrated in fig. 6, with a big difference in the gradient value at a depth of about 115 m. Above that horizon

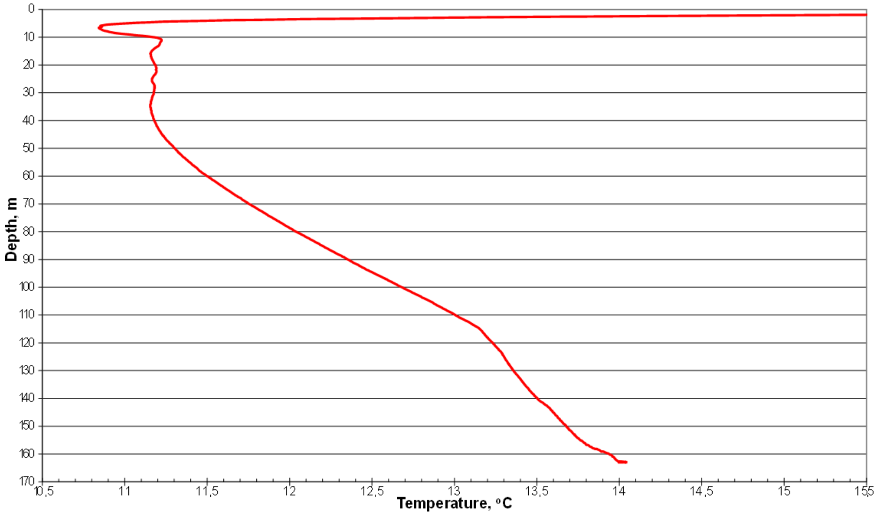

Fig. 4. Measured temperature profile of borehole heat exchanger P-2 (double u-tube) in terms of thermal stability

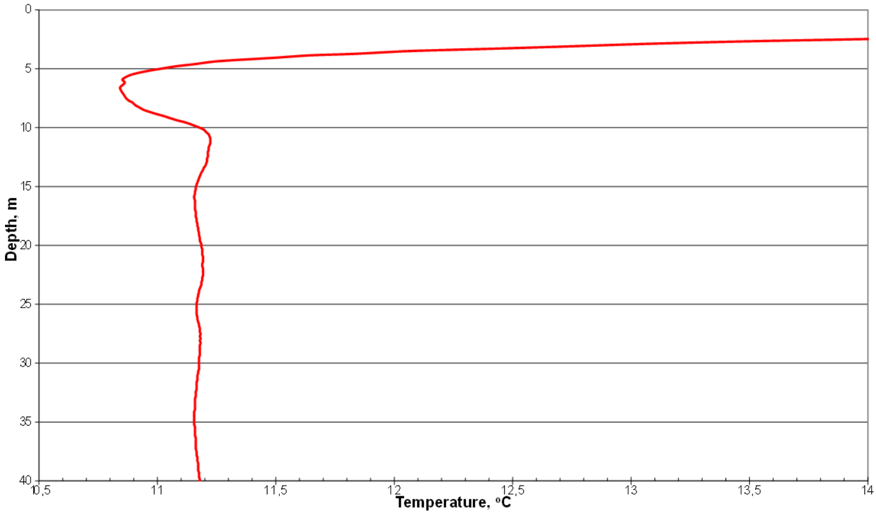

Fig. 5. Measured temperature profile of borehole heat exchanger P-2 in interval 0-40 m

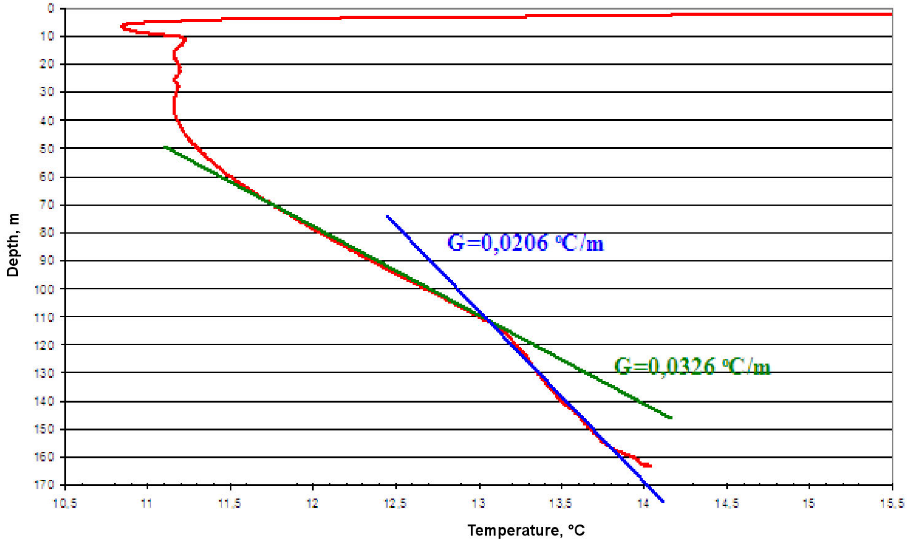

Fig. 6. Geothermal gradient in the hole P-2 (double u-tube) in terms of thermal stability

the gradient value increases, ad so the heat more easily propagates in the rock mass below 115 m of depth, thus producing a lower geothermal gradient in line with the Fourier law:

$$q = -\lambda \cdot \nabla T \tag{8}$$

where q is natural heat flow of Earth's and ∇T is a temperature gradient. On the basis of measurements an average temperature of profile in interval 0-162 m was determined. It equaled to 12.37°C.

The measurement of average temperature in boreholes was based on a long-term circulation test of heat carrier. The results of measurements for borehole P-1 (single u-tube) was presented in fig. 7. Circulation lasted 17 hrs and the measured average temperature of heat carrier in the last hours of circulation equalled to **12.88°C** at ambient temperature about 15.65°C.

The thermal reaction test was worked out on the basis data from the borehole. The results of temperature measurements during the TRT in borehole P-1 (single U-tube) were presented in fig. 8. The averaged heating power over the entire heating cycle for borehole P-1 was equal to 8617 W.

The effective thermal conductivity of rocks in the profile in which borehole P-1 (single U-tube) was drilled and thermal resistance of the BHE were determined on the basis of the test and equaled to **2.18 $Wm^{-1}K^{-1}$** and **0.21 mKW^{-1}**, respectively. The lithological profile with weighted average (thickness) values of thermal parameters for borehole P-1 (single U-tube) was presented in Table 2. The calculations were conducted after Gehlin (2002) and Sanner at al. (2005).

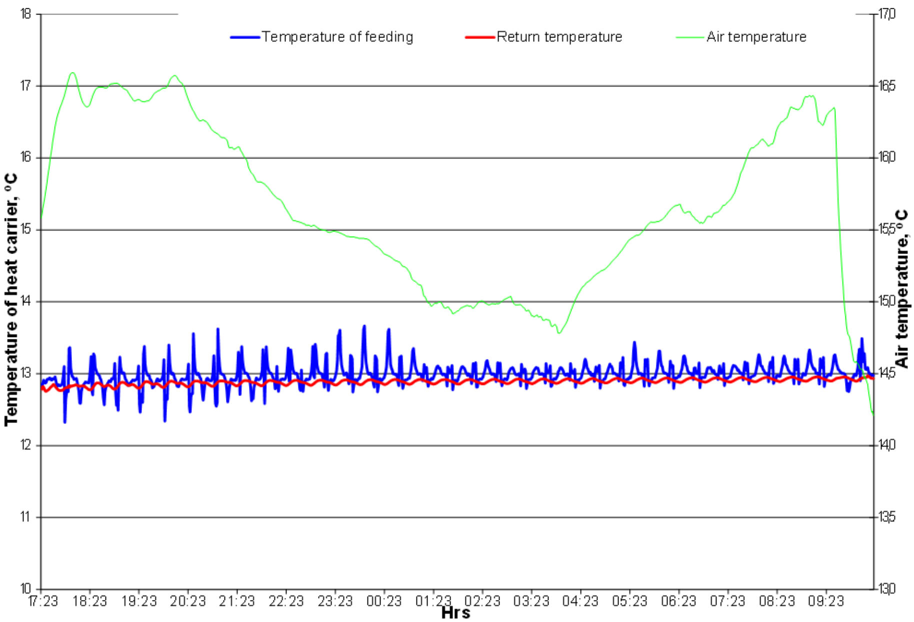

Fig. 7. Results of measurements of average temperature of rock mass for borehole P-1 (single U-tube) before TRT

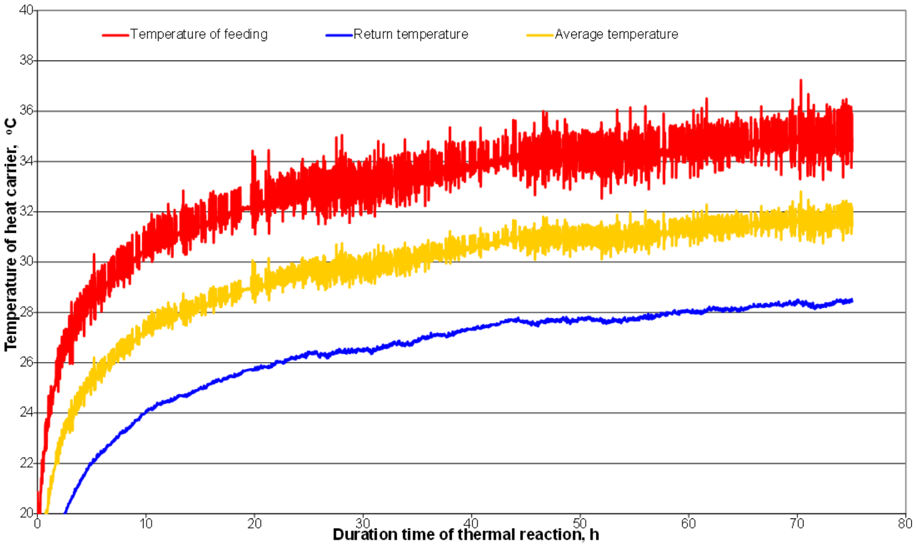

Fig. 8. Results of temperature measurements during TRT of borehole heat exchanger P-1 (single U-tube)

5. Numerical calculations

The partial differential equation describing the phenomenon with the use of equations 1 to 4 do not have any analytical solution. The issue can be solved in a simplified way (Beier, 2011) or numerically. From among the simplified analytical and numerical models of borehole heat exchangers, the numerical models have been most developed recently. Attempts are made to shorten the time of calculations and improve the accuracy of solutions. The proposed literature-based numerical models considerably simplify the task (Raymond et al., 2011; Lee & Lam, 2008). The applied numerical models are limited to 2-dimensional models (Raymond et al., 2011). Diersch et al. (2010) and Al-Khoury et al. (2010) describe a 3-D model with 1-D flow of the heat carrier, which does not account for viscosity changes with temperature. In Polish literature, the description of a full 3-D model can be found in Gonet (2011) and Gołaś & Wołoszyn (2011).

The calculations in this paper were made with the use of a commercial, fully 3-D calculation package. Modeling of temperature and fluid flow distribution in the analyzed object is a demanding calculation problem. This mainly results from the big size of the analyzed area and so a big number of finite elements. The numerical calculations were made with the package ANSYS CFX based on the finite volumes method.

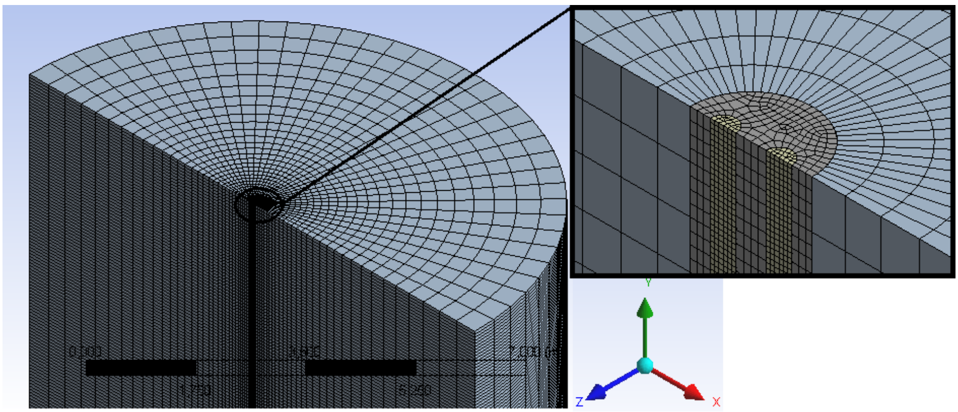

Fig. 9. The control volume grid

The package Ansys CFX is software dedicated to solving problems related with mass and heat transport. On the basis of the finite volumes method this package allows for solving partial differential equations with complicated boundary conditions. It should be born in mind that the obtained solutions are burdened with errors resulting from the approximated character of the method. Simplifications made when working out the model, facilitate its description and yet have influence on the accuracy of the solution. Far-fetched simplifications may result in ignoring significant properties of the real system, whereas a more complex mathematical model may create errors in solution owing to the complex calculation process (Lee & Lam, 2008; Li & Zheng, 2009).

The distributions of thermal fields over the entire volume of the analyzed rock mass and borehole heat exchanger were obtained from the numerical calculations. Fig. 11 illustrates the distributions of thermal fields transversely cut by plane „xz” at the depth of 60 m, 120 m and 178 m, respectively. Fig. 10 gives a comparison of thermal distributions. The variability of temperatures in time at various depths and at different distance from the borehole axis was presented in fig. 12. The first observations reveal that thermal processes taking place in the rock mass have a relatively fast flow of heat in a close vicinity of the borehole heat exchanger, to relatively slow down in the successive rock environment. Fig. 13 shows temperature changes of the heat carrier at the inlet and return from the borehole heart exchanger. The plot in frig. 14 represents changes of average temperature at the inlet and return, from measurements and from simulations, respectively. The differences result from, among others, the similar character of the method, assumed properties of the rock mass and the boundary conditions.

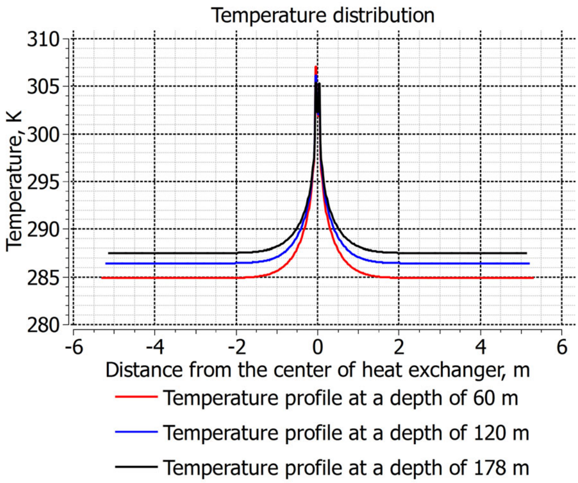

Fig. 10. Temperature changes at depths of 60 m, 120 m, 178 m

6. Conclusions

1. The presented simulations enable effective solving of models in the form of Fourier-Kirchhoff, and Navier-Stokes equations as well as the equation of flow continuity and heat exchange equation for the analysis of the heat exchange problem in a borehole heat exchanger conditions. The reliability of simulation necessitates identification of parameters of the model, especially the boundary conditions.

2. The empirically determined effective thermal conductivity of a borehole heat exchanger equaled to 2.18 $Wm^{-1}K^{-1}$, whereas the thermal resistance of the exchanger at 180 m of depth was 0.21 mKW^{-1}. Values obtained from numerical calculations were 2.21 $Wm^{-1}K^{-1}$ and 0.22 mKW^{-1}, respectively. The causes of the errors could be numerous. The thermal response test of the rock mass gives allowance ± 5% (Sanner et al., 2005). It should be remembered that the accuracy of the applied numerical method greatly depends on the quality of the finite elements grid, which owing to the magnitude of the model and the related time of calculation was not sufficiently accurate. It should be observed that assuming appropriate boundary conditions and thermophysical conditions of the rock mass is both important and difficult to perform.

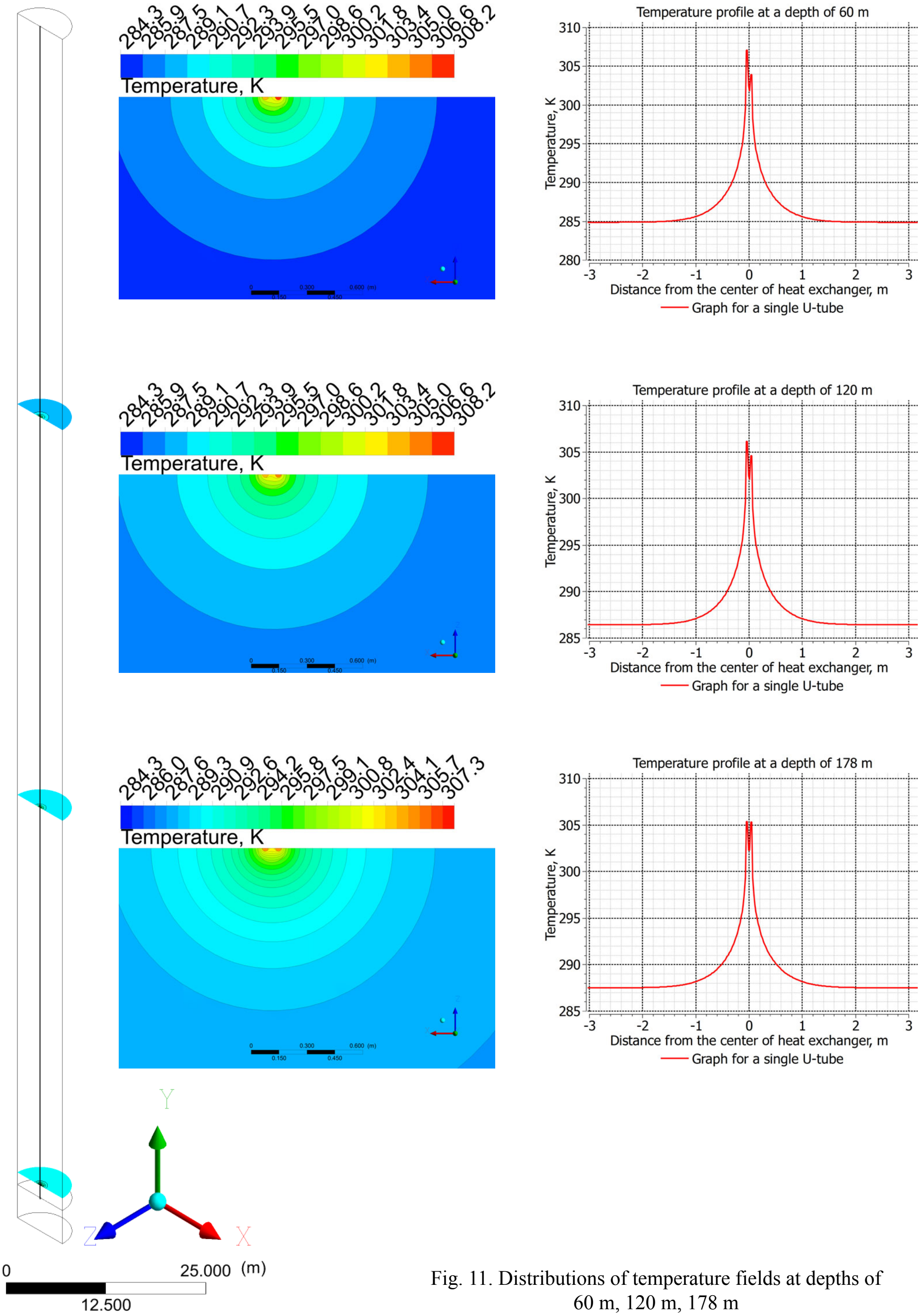

Fig. 11. Distributions of temperature fields at depths of 60 m, 120 m, 178 m

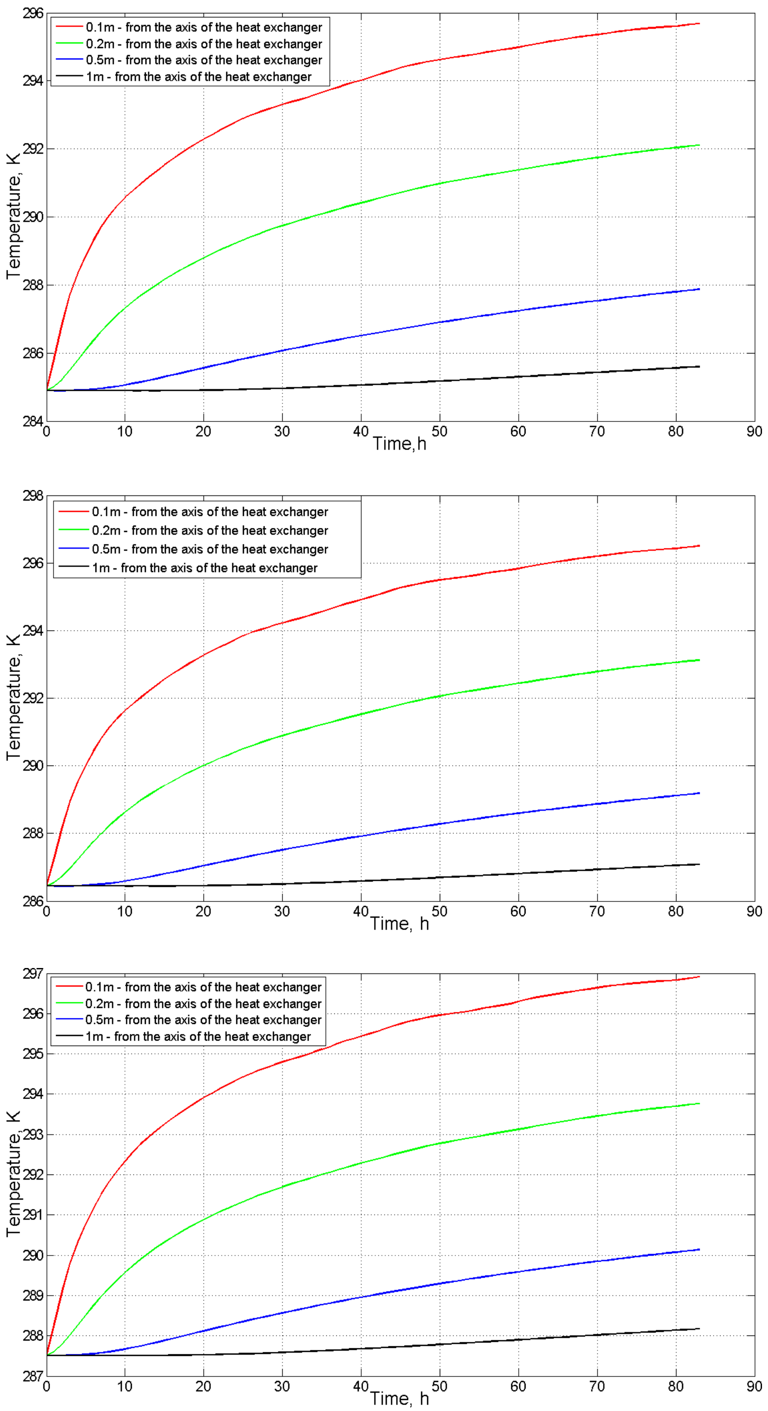

Fig. 12. Temperature changes in subsurface at a depth of 60 m, 120 m and 178 m, respectively

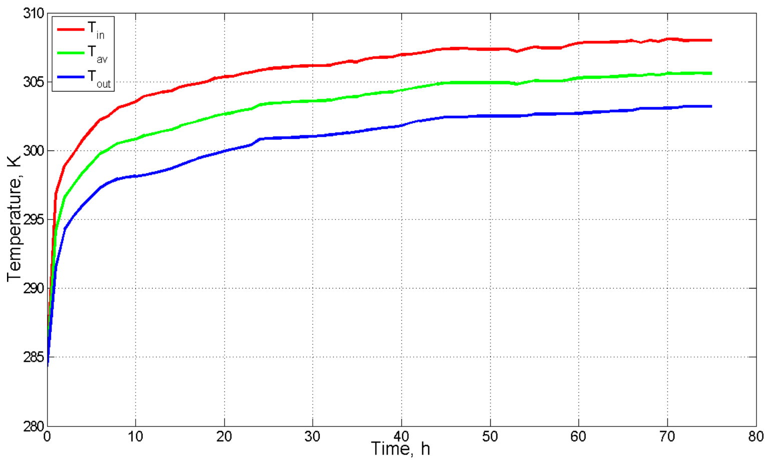

Fig. 13. The temperature changes on the supply and return of borehole heat exchanger

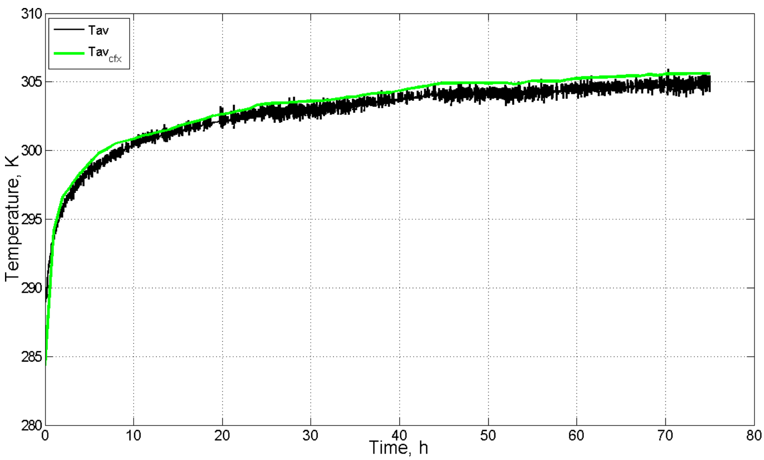

Fig. 14. Average heat carrier temperature changes for measurement and simulation data

3. The results visualized in the form of plots and temperature distributions confirm that the calculation method is correct and the presented results should be treated qualitatively. Obtaining a good thermal conductivity result was connected with long-lasting calculations and tedious preparation of the model. The field analyses were prepared in a few days but it took several months to complete the simulations. Further works are conducted in view of shortening the time of calculations and maintaining a low level of error.

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