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AN ANALYSIS OF A TEMPERATURE CHANGE IN A CROSS-SECTION OF BOREHOLE HEAT EXCHANGER***

1. INTRODUCTION

Borehole heat exchangers (BHE) are systems enabling energy flow between the ground and the surface. To simplify the mathematical model describing their work, they are often presented as a linear heat source of the same temperature all along the exchanger. That simplification allows calculating theoretical BHE temperature changes during transporting energy to or from the rock using basic analytical methods. A drawback of this approach, however, is the assumption that the temperatures are constant both along the exchanger and in its horizontal cross-section.

The analysis of temperature fluctuations in BHE sealing cement is possible by applying numerical simulations or laboratory models. Computer simulations are based on law of conservation of energy, where energy flows through the cross-section of BHE cells, into which the system is divided. Another method is to obtain the values of temperature at certain points of sealing cement by use of sensors acquiring data from the cross-section of the laboratory model of BHE. The paper presents steps from building a theoretical model of BHE to obtaining temperature distribution results.

2. BASIC PROBLEM

The construction of BHE is a hydraulic pipe from polyethylene high density, set up to the well to about 150 meter depth. The branches of the pipe are solid by sealing grout with the surrounding rock [1, 3–5].

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The most popular type of BHE is construction single U-pipe. Other constructions are less common, because:

- double U-pipe is more difficulty through put branches of pipes to the well and more expensive (economical aspect),
- two centric pipe giving some problems through connecting each pieces of pipe (high dimension of external pipe requires polydyfusial connection techniques) and good quantity thermal isolation internal pipe (this generating high costs).

As a consequence of large problems, coast, accessible materials and equipment to polydyfusial connecting material the single U-pipe construction of BHE is most popular types, uses common to small and large installation and to cooperating with heat pumps.

Additive problem through constructing centric BHE is very high conductivity internal pipe and loss of heat from this area (the difference of temperature fluids in the inlet and outlet BHE, when the internal pipe has a high thermal loss, is low and efficiency BHE is low too).

The works each of types of BHE might explain by circulating fluids first in the bottom and next to the surface land. The most recipe of fluid is a 30% solution of glycol with water. This mixture prevents from freeze up fluid (sometimes heating pumps decrease the temperature of the fluid below 0°C). The energy is carrying by fluid in branches and renew with wall of pipe. Next through the sealing grout it is conducted to/from ground around borehole exchangers.

The construction of BHE lets it work in two ways. First case, called heating mode or cooling ground, is when the energy is transferred from rock to fluid and then up to the receiver set at the surface. In this case low temperature energy (from –5°C to 15°C) is taken through heat pumps. Second case, called cooling mode or heating rock, is when the heat is transferred from an object at the surface down to the rock. Here, the working of installation might be divided by two approaches: active and passive. Active ways base on using waste heat from a heat pump. The temperature of fluid from a condenser of a heat pump ranges from 25°C up to 40°C. Passive ways are possible when the temperature of the source on land (air temperature) is higher than the temperature of rock. Recuperation of the heat in the ground (case of transferring heat into the rock) improves the efficiency of a whole installation.

The case of work during with the heat is transporting to the rock is used to TRT – Thermal Response Test. This research has to show thermal parameters of BHE components and rock surrounded BHE. Of thus parameters are thermal resistivity of BHE and thermal conductivity of subassembly BHE-Rock. The data from TRT are useful, when BHE was taken how linear heat source. It let to count thermal conductivity (1). Calculation of thermal resistivity requires additionally the known average specific heat of rock in depth of BHE (2):

$$\lambda = \frac{P_{\mathrm{TRT}}}{4 \cdot \pi \cdot H_{wo} \cdot k_{\mathrm{TRT}}} \tag{1}$$

$$R_b = \frac{H_{wo}}{P_{\mathrm{TRT}}} \cdot (T_{owc} - T_o) - \frac{1}{4 \cdot \pi \cdot \lambda} \cdot \left[\ln(t) + \ln\left(\frac{4 \cdot \lambda}{r_{wo}{}^2 \cdot \rho_g \cdot Cp_g} \right) - 0.5772 \right] \tag{2}$$

The temperature of BHT is an accepted value of average temperatures fluid flow to inside and outside branches of BHE (3) (from it simplifying it results that one value the temperature of the whole exchanger be represented):

$$T_{owc} = \frac{T_{\text{in}} + T_{\text{out}}}{2} \tag{3}$$

Using the above-mentioned simplification, while describing the behavior of BHE during a TRT test, eliminates the possibility of identifying changes in temperature in cross-sections along BHE at different depths. In consequence, the field of temperature in a cross-section of BHE creates concentric circles, in the center of which, there is BHE. In reality, the temperature of the branches is identical only at the bottom of BHE. The largest difference in temperature values can be noticed near the outlet of branches. The hypothetic sketch of the temperature field is presented below (Fig. 1).

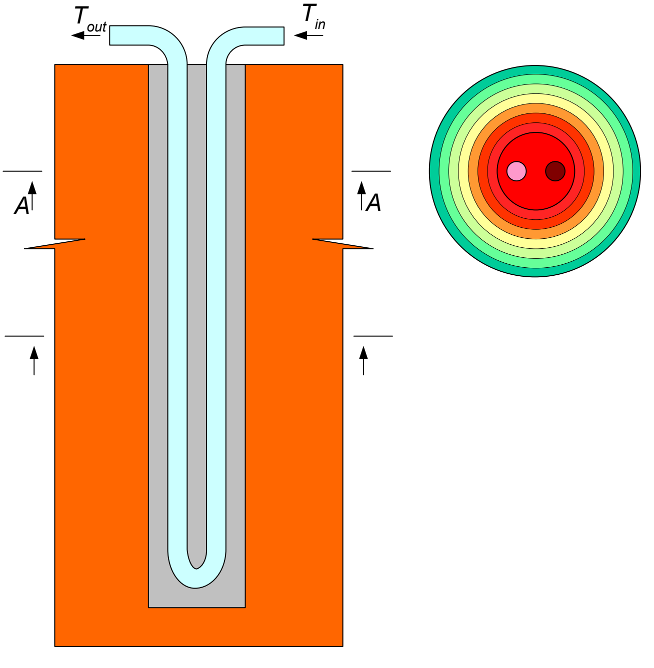

Fig. 1. The hypothetic schedule of temperature of around BHE, accepted with foundations of breaks up of energy during the execution of test peaceably TRT

Other interpretation on BHE is possible if it accepts in function of depth of exchanger the changing value of the temperature (the length of lines). Then, the value of the average of temperature of cross-section of BHE mighty mark as average the temperature of fluid flowing to bottom of BHE and coming back on surface, on given depth (4):

$$T_{owc}(H) = \frac{T_{\text{in}}(H) + T_{\text{out}}(H)}{2} \tag{4}$$

These temperatures are possible to determine with support of numerical calculations (calculating a decrease of the carrier fluid's temperature inside the branches during its flow) or to measure with a declining sensor – the one that should be used during a TRT test, but with no unlocking the hydraulic route of BHE. The course of temperature changes in case when BHE is working in warmth-storing mode, is presented in Figure 2. The scheme of the temperature field in this type of interpretation is introduced in Figure 3.

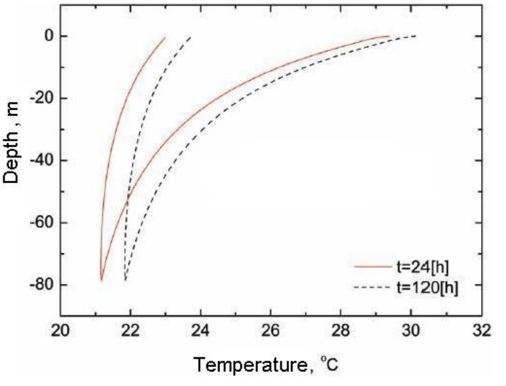

Fig. 2. The course of changes of value temperatures in branches of BHE type single U-pipe got in mode storing energy for 24 h and 120 h of work [2]

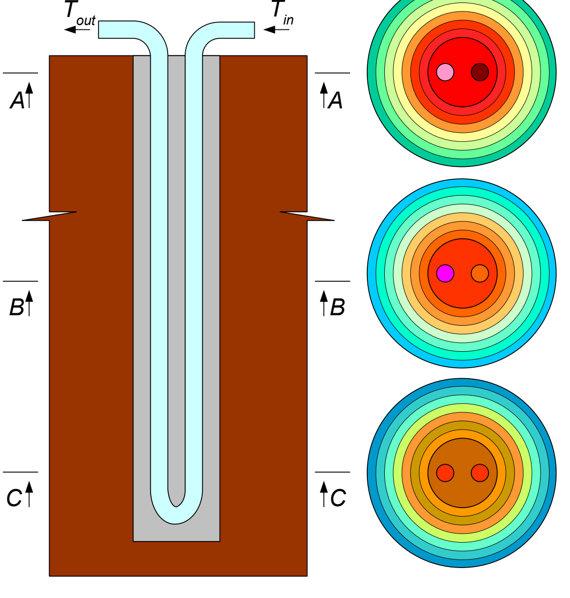

Fig. 3. Hypothetic schedule of the temperature of around BHE after regard the changes of value of average temperature transverse section exchanger in function of depth [1]

It the foundation, that the BHE is the source of warmth about variable of temperature (in function of depth) made difficult in the interpretation of information about his behavior. However it is to analysis of changes of field temperature basis in his transverse section in function of time. Analysis this, is possible to conduct by computer. Her effect is the simulation of changes of the temperature field which is showed by mathematical equations. The empirical verification of correctness of working constructed simulators is possible on real model of transverse section the BHE.

3. LABORATORY MODEL OF THE BHE CROSS-SECTION

The model of the BHE cross-section of a single U-pipe construction was equipped with 32 temperature sensors of the accuracy ±0,1°C (Figs 4, 5). During measurements, the results were read and recorded in periods of 2 s. Created model enables differentiating the temperature of the flowing fluid, simulating behavior of the exchanger at different depths. The temperature of the outer layer is kept constant. It is also possible to simulate the reverse working mode (where the energy comes from the surrounding ground). The obtained results were put in the table and the graphic interpretation of the temperature field changes was created using the "Surfer" software. The laboratory model of the BHE cross-section was created thanks to financial support from grant-in-aid no. 15.11.190.623.

Fig. 4. Laboratory model of cross-section of BHE

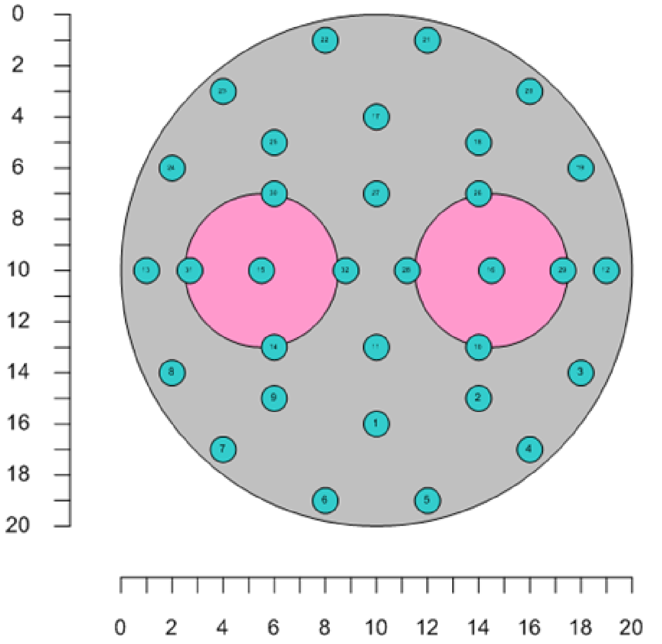

Fig. 5. Distribution of sensors of temperature in cross-section of BHE

The simulating of the BHE work was divided in two stages [6]:

- The first hugging time, in which liquid circulating in exchanger it will not execute one full circulation.
- The second, which begins after total exchange one volume of liquid in BHE. The flow of warmth in every section of exchanger sets between rock and two lines then.

In reality the transportation of warmth setting in transverse section of exchanger of warmth in significant way it influences on quantity of passed on energy to rocks. Phenomenon this sets in function of depth of exchanger as well as radial location surrounding him rocks in relation to transporting in two directions the liquid lines. Thanks to building of laboratory model possible the qualification area of temperature will be empirical measured, graphic their visualization and also verification of correctness of numeric models of BHE. The changes of temperature field of transverse section of BHE during first stage of work were introduced on Figure 6. Individual sequences on drawing these illustrate schedule the temperature area in temporary even intervals 4 min. The temperature in lines of exchanger carried out 22°C and 40°C suitably. The temperature of external surface of model has been stabilized and provide for on level 22°C.

Figure 7 shows the changes of temperature in second stage of work. The temperature of liquid in lines of exchanger carried out 36°C and 40°C suitably. The temperature of the external surface is in this case the same as before (22°C). The schedule of temperature field in longer period of time (1–4 h of work) near provide for in lines of exchanger the temperatures how earlier (36°C and 40°C) was introduced in Figure 8.

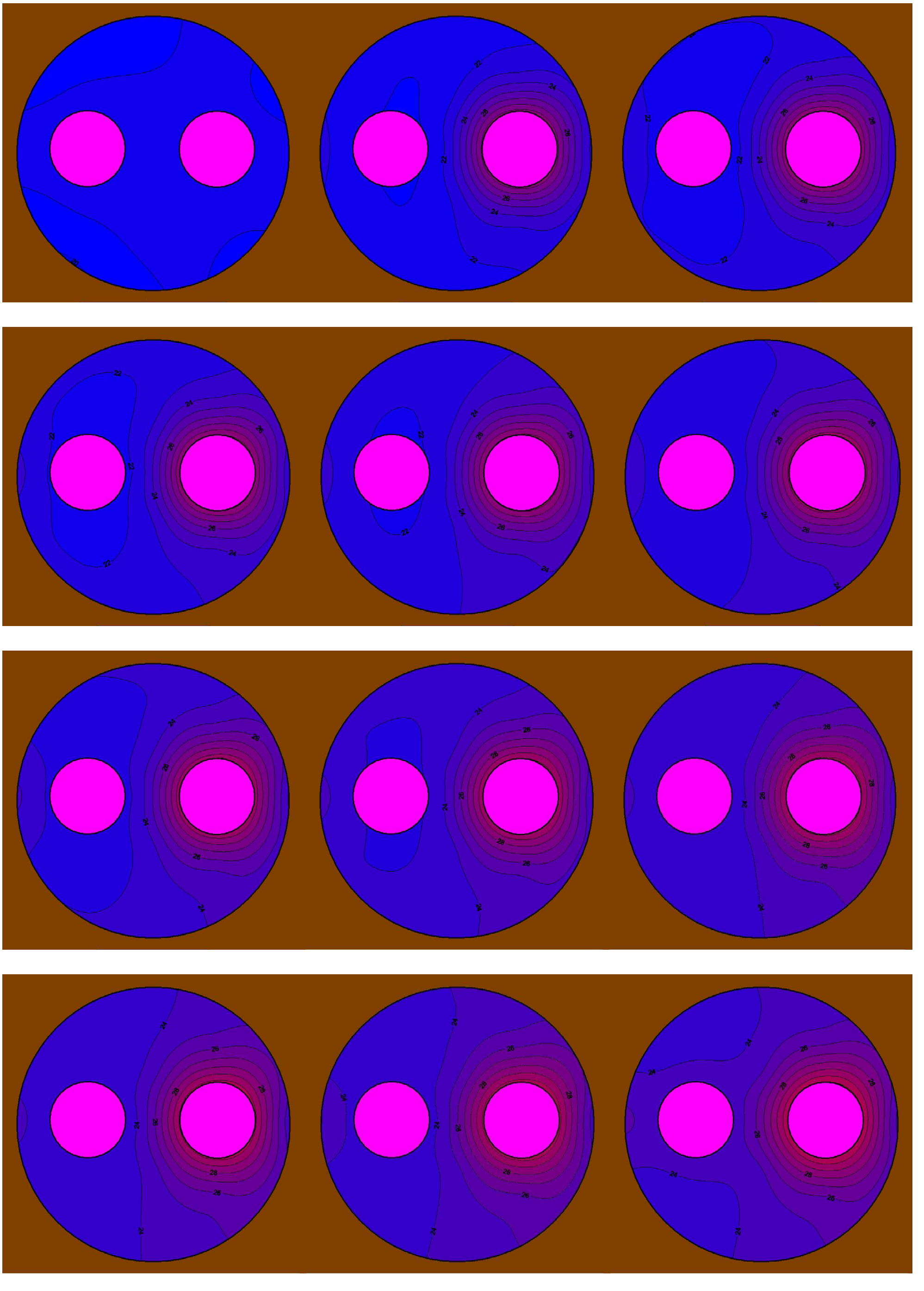

Fig. 6. The sequences of schedule of temperature field in temporary even intervals 4 min, in the first stage of work of BHE, one line = 1°C

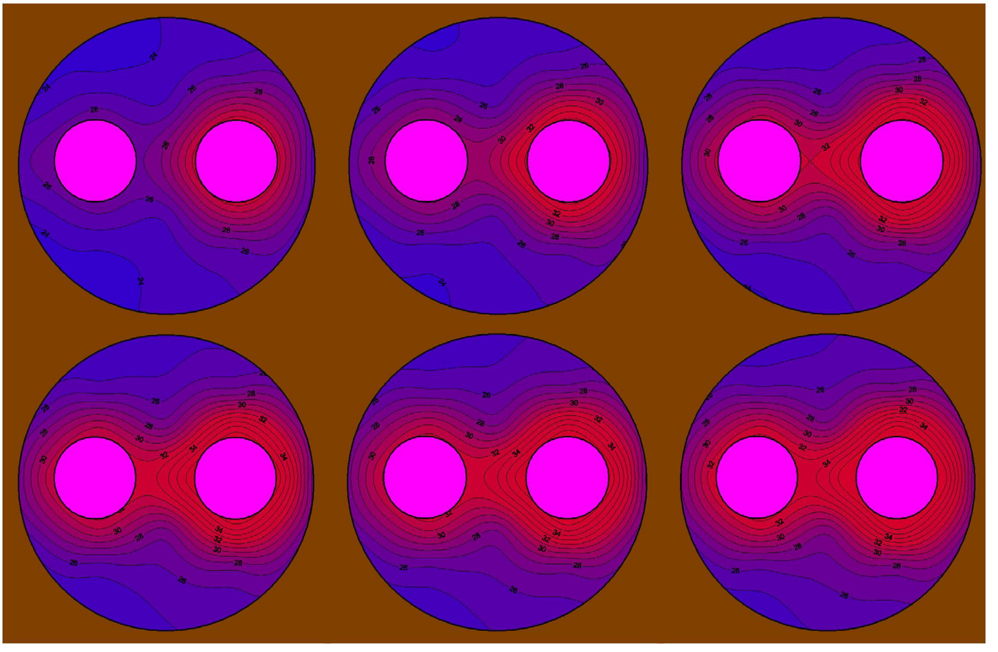

Fig. 7. The sequences of schedule of temperature field in temporary even intervals 4 min, in the second stage of work of BHE, one line = 1°C

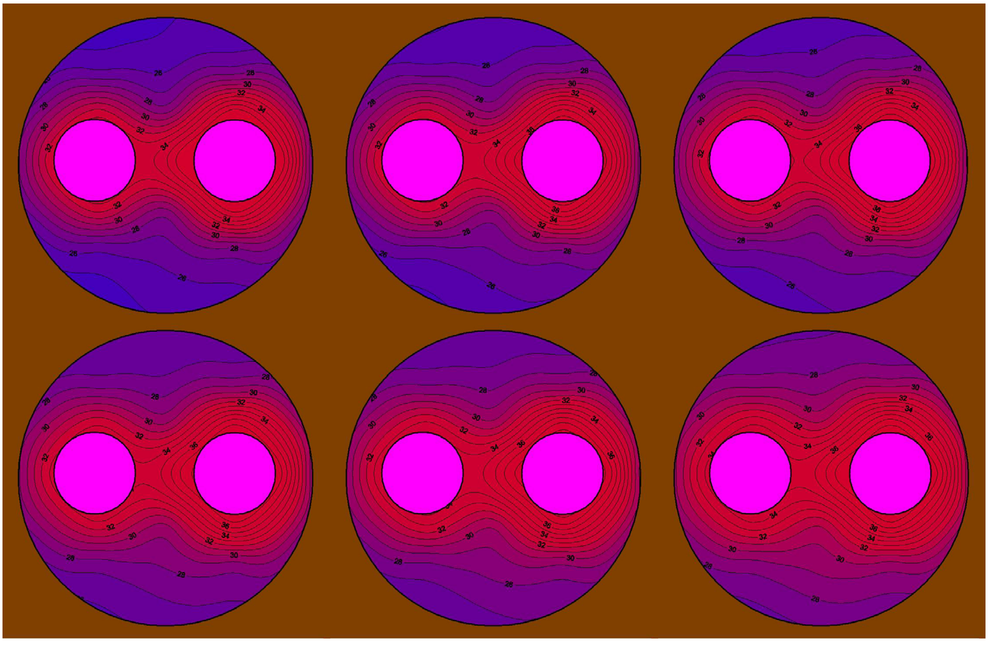

Fig. 8. The sequences of schedule of temperature field in temporary even intervals 30 min, in the second stage of work of BHE (from 1 h to 3 h 30 min), one line = 1°C

Built laboratory model permits on many kinds of simulations of behavior of BHE both in mode taking how and storing heat. The got results let the possibility of comparison the received information on road of numeric simulation from empirical image the flow of energy. Conducted investigations appear the possibility of qualification of behavior the different type of exchangers. In this aim necessary realization of different type of models is (double U-pipe, concentric exchanger).

4. CONCLUSIONS

1. The laboratory model of a cross-section of borehole heat exchanger allows simulating conditions in real exchangers at any depth.
2. Temperature fields distributions presented in the paper prove that there is a difference between theoretical values of temperature and real values.
3. The temperature of the lateral surface of the exchanger changes depending on its position in relation to the branches of the exchanger.
4. The mean temperature of the fluid flowing inside and outside the exchanger does not represent the average temperature of a BHE cross-section, neither the whole exchanger. This value is considerably bigger than the real value.
5. Obtained results allow further interpretation of the collected data along with describing it with mathematical equations.
6. The field of temperature proves the legitimacy of applying concentric and double u-pipe borehole heat exchangers.

Nomenclature

Cp_g – average heat capacity (mass) of rock [J/(kg·K)],
H_{wo} – depth of BHE [m],
P_{TRT} – power delivered to BHE during TRT [W],
R_b – thermal resistivity of BHE [m^2·K/W],
r_{wo} – radius of BHE [m],
t – time of work of BHE (time of TRT) [s],
T_{in} – temperature of liquid influencing to exchanger [K],
$T_{\mathrm{in}}(H)$ – temperature of liquid flowing to the bottom of exchanger [K],
T_o – average temperature of rock before beginning the transportation of heat [K],
T_{out} – temperature of liquid sailing out from exchanger [K],
$T_{\mathrm{out}}(H)$ – the temperature of liquid flowing to the top of exchanger [K],
T_{owc} – temperature of BHE [K],
$T_{owc}(H)$ – temperature of BHE in depth function [K],
λ – thermal conductivity [W/(m·K)],
ρ_g – average density of rocks [kg/m^3].

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