COMMUNICATIONS

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ANALYSIS OF TRANSMISSION PHENOMENA IN LOW-POTENTIAL HEAT TRANSPORT BY HEAT PIPES IN THE DEEP- BOREHOLE SIMULATOR

This article presents a proposal of a simulator for low-potential geothermal heat transfer by means of heat pipes into the heat pump exchanger section. On this device the research on transmission phenomena at different temperatures at the simulator inlet was done. Measurements were taken at various temperature and pressure parameters of carbon dioxide as a working substance in the heat pipe. The paper contains experimental measurements on the simulator for low potential heat transfer and their analysis, theoretical analysis of phase changes in carbon dioxide in the heat pipes depending on changes in pressure and temperature. Simultaneously, the impact of these two quantities on other parameters of the system will be analyzed, namely, input and output temperatures of the coolant in the heat exchanger and cooling of the surrounding rocks. In the conclusion are laboratory results and the CFD simulation model of low-potential geothermal borehole.

Key words: heat pipes, low-potential heat, deep-borehole simulator, geothermal heat

1. Introduction

At present, considerable attention is paid to the use of low-potential geo heat by means of heat pumps obtaining the low-potential heat by forced circulation pumps. One possibility to increase the intensity of low-potential heat transfer is the application of heat pipes (HP) placed in deep boreholes.

2. Simulator of deep borehole

The device for the use of low-potential geothermal heat without forced circulation of the heat medium in a deep well pressure is equipment using domestic energy resources. Such use has a direct impact on the environmental protection through the reduction in CO_2 production in providing thermal comfort.

The project innovativeness lies in the use of low potential geo heat for heating without any circulating pump to provide warm fluid flow in a deep borehole or its model.

The purpose of the designed device is to simulate transfer of low-potential heat from rocks by means of a collector with cooling fluid and heat pipes in laboratory conditions. It is also possible to perform measurements of heat flows at identical input temperature conditions and at different heat pipes filling (CO_2, NH_3) at various pressures during filling the pipes.

Fig. 1 Simulator

The device (simulator Fig. 1) for the transport of low-potential heat through stage conversions in the evaporation and condensation sections of the pipes at temperatures below 0 °C enables the development of research activities for the verification of manufacturing technology of heat pipes suitable for the use of low-potential geo heat in laboratory conditions. Individual components of the device allow the investigation on thermo kinetic parameters of heat transport from rocks to the heat carrier on the model. The

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device enables a realistic modeling of heat flows from rocks to the heat carrying medium.

This device, which was designed as a scale model of two deep wells, each of which carries away geo heat by means of other technology and other heat carrier. The basic idea lies in the simulation of geoprocesses, i.e. in accumulation of heat in rocks through heating and subsequent carrying the heat away with the use of both existing and new technologies.

3. Construction of the borehole model

The borehole model consists of several simple components. The borehole itself is a 200 mm polyethylene tube which is 5 m high, Fig. 2. The polyethylene tube of diameter 500 mm and 5 m high represents the neighborhood of the cylinder-shaped borehole. A smaller tube is coaxially secured in a larger one by means of insert connectors. Four heat pipes with carbon dioxide as a working fluid supplied from a gas bottle are inserted into a borehole (200 mm polyethylene tube). The heat pipe surrounding is filled with bentonite in which heat is accumulated and subsequently taken away through the heat pipes. The inner annular space is filled with damp sand, (rock neighborhood of the borehole) whose coefficient of thermal conductivity is 1.63 $W.m^{-1}.K^{-1}$.

The outside pipe circumference (500 mm) is spirally wound by a heating cable whose output is 10 $W.m^{-1}$ (it substitutes accumulation of Earth's heat). The cable diameter is 6 mm and the pitch is 30 mm (Fig. 2) [1].

NiCr-Ni thermocouples were used to observe the course of temperatures in the borehole average and height, Fig. 3. Thermocouples are touch temperature sensors consisting of two different metals welded together. There is surface tension on the weld joint whose quantity depends on the temperature.

For the simulator we will use 26 thermocouples which will be connected to the Ahlborn Almemo measuring instruments. The control panel is connected to a laptop with the software AMR
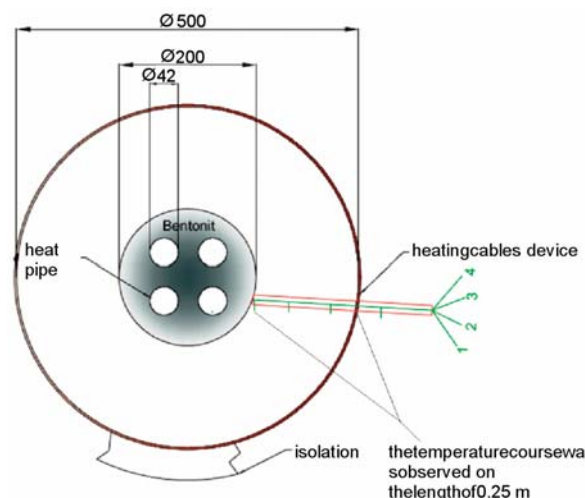

Fig. 3 A cross section of a model borehole and the way in which thermocouples are introduced

Wincontrol 6, that records all the data in Excel within pre-set time intervals. The measuring station was located on the platform 4 m above the ground. The length of individual thermocouples differs with regard to their position in the simulator. The bunch of 26 thermocouples is kept in a protection sleeve for their better arrangement towards the control panel.

It is important to know the phase transformation of carbon dioxide in the bottle as the filling of heat pipes is provided from a pressure bottle. The bottle was weighed after each filling of the heat pipes and we could follow changes in its mass. We are thus informed on the total amount of CO_2 (kg) in the heat tubes.

The simulator is designed so that the evaporation part of the heat pipe is introduced in the heat exchanger and the coolant (Thermal G) in the exchanger carries away the heat from the working medium (CO_2) in the heat pipe, Fig. 4. The coolant in the exchanger washes the heat tubes surfaces in which condensation of gaseous CO_2 occurs. Subsequently, the condensate flows down
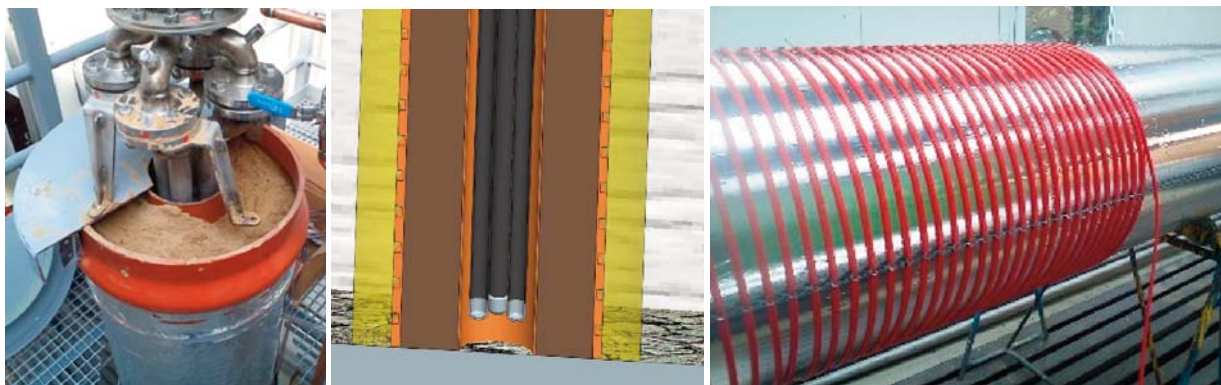

Fig. 2 Heat-pipe embedded in borehole models and electric heating cables as natural surroundings of the borehole substituting the Earth's heat

the heat pipes walls to the bottom part where CO_2 is in a liquid form and the whole process is repeated. The process without forced circulation can work only at a certain pressure and temperature which corresponds to the saturation curve [2].
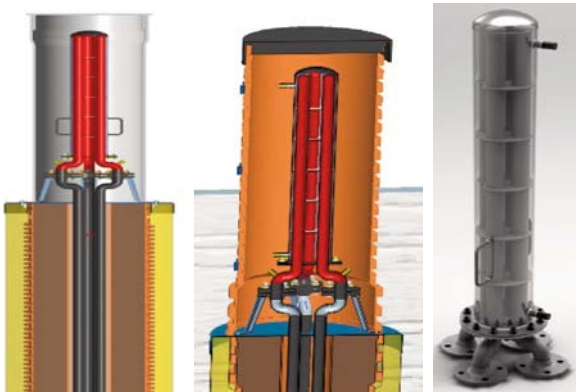

Fig. 4 Upper part of heat pipes placed in heat exchanger

CO_2 is in a gaseous form at the initial pressure of 2.37 MPa and at the temperature of 37 °C. In Fig. 5 the red point shows the concrete state of gas in a phase diagram. In this situation no change of state occurs. The process described above can occur only when we move along the saturation curve. It is, therefore, necessary to increase the pressure or to lower the temperature. After the CO_2 gets into a state of saturation, it will be necessary to maintain this state by means of heating cables = the Earth's heat. The achieved equilibrium between the Earth's heat supply and its take away enables a long-term heat take away in the heat exchanger.

The simulator condition before the measurements was as follows:
- pressure of CO_2 in the heat tubes: $p_0 = 2.37$ MPa
- the average temperature in the simulator (average value of 24 thermocouples placed along the simulator height and diameter – borehole cylinder): $t_0 = 37$ °C,
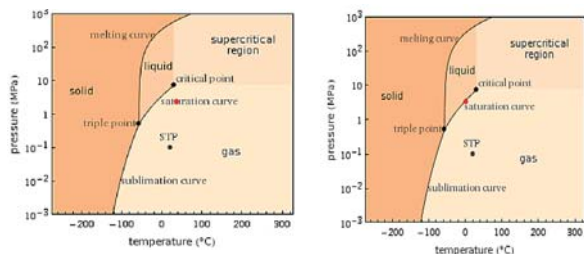

Fig. 5 Phase diagram showing CO_2 specific conditions [3]

The average temperature in the simulator before starting the measurement did not correspond to the actual soil temperatures at the depth of 150 m,because the temperature increases with depth according to the geothermal gradient by 3 or 4 °C for 100 vertical meters [4]. From 30 m and lower the temperature continuously increases by 1 °C for every 32.7 m. At the depth of 3 km it is about 100 °C. Preset average temperature in the simulator $t_0 = 37$ °C corresponded to the depth of approximately 1000 m. For the purpose of measurements and simulation of the most frequently constructed wells at the depth of 150 m, we needed during the measurement to achieve the temperature from 9 up to 12 °C.
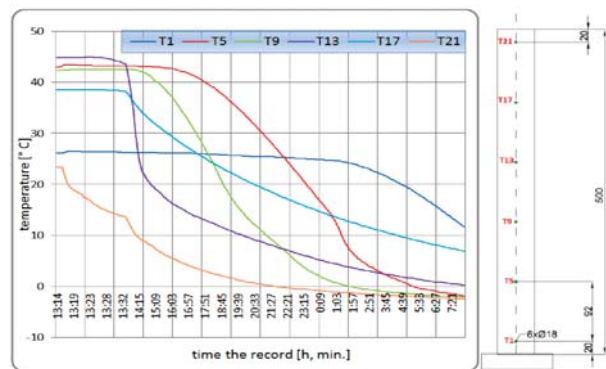

Fig. 6 Recorded drops in temperatures

We will increase the initial pressure $p_0 = 2.37$ MPa to $p_1 = 3.5$ MPa. After the increase in pressure, the temperature drop in the simulator was monitored. When the average temperature dropped to $t_1 = 9.11$ °C (19 hrs. of record), we turned on the heating by means of electric heating cables alongside the simulator-borehole height. At this temperature the pressure was 3.04 MPa. To be able to exactly determine the CO_2 temperature we have to consider only those thermocouples that are located in the vicinity of the heat pipe (Fig. 6).The total average temperature gives us an idea of the soil temperature, but for the average temperature of the working medium only the thermocouples placed very close the heat tube should be taken into account.

We obtain 1 kW of heat output from approximately 12 to 18 m of a borehole [5]. If we choose the value of 17 m for the output of 1000 W we get from 1 m borehole approximately 60 W. The heating by means of heating cables alongside the simulator is divided into 3 sections, each of which is connected to the power supply RAT whose performance is set to the value of 60 W. Such an output suffices to maintain the average temperature in the simulator. Fig. 6 shows the section in which temperatures begin to drop and the state of "quasi-equilibrium" begins. The temperatures level off.

The actual borehole is an infinite cylinder in which the heat spreads in the direction of the temperature drop, i.e., to the point where the heat is carried away by means of chosen technology. Since in laboratory conditions an infinite rock cylinder cannot be measured, heat must be supplied to the borehole in some other way. This is provided by means of electric heating cables that heat the sand (rock) in the borehole neighborhood.
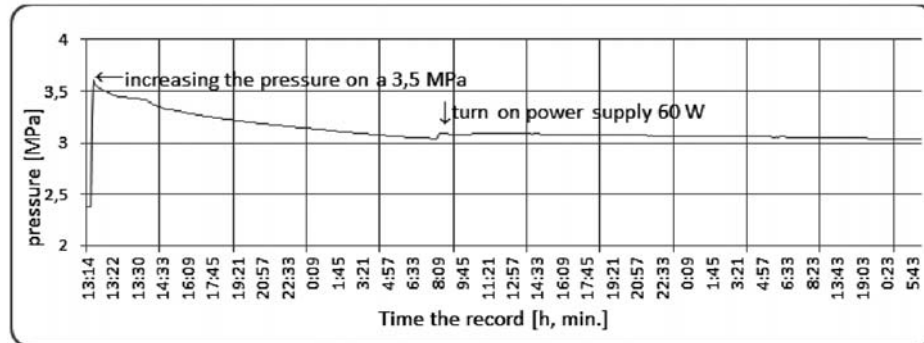
Fig. 7 Pressure increase in the tubes and its several-hour drop corresponding to temperature drop in the simulator

Fig. 7 illustrates the pressure course of CO_2 in the simulator from the pressure p_0 to p_1. Pressure drop lasting several hours resulted in the whole simulator cooling. When the temperature in the simulator increases after switching on the electric heating cable, there was a slight increase in pressure.

Due to the pressure increase (to 3.5 MPa) we achieved the average temperature drop (by 27.9 °C) in the simulator (the temperature corresponding to the depth of 150 m). Using heating cables we ensured the stabilization of temperature and pressure in the simulator (delivery of 60 W during 24 hours.) We thus achieved the average temperature difference $\Delta t = 0.56$ °C in the heat exchanger. The specific heat capacity of the coolant Thermal G is 3300 J.kg^{-1}.K^{-1} and the average flow rate recorded during the measurement was 11 kg.min^{-1} = 0.18 kg.s^{-1}. We calculated that the heat carried away during the state of equilibrium was $\dot{Q} = 332$ W.

4. Numerical Simulation of Borehole Model for the Transport of Geothermal Heat

Numerical models (Fig. 8) were developed on the basis of a real model of the simulator designed to simulate geothermal heat with forced circulation.

Fig .8 External and internal structure of borehole simulator

The geometry of simulator model was created in the Gambit program according to the already designed construction. Having meshed the model, the boundary conditions were set (fluid geometry, solid material geometry, velocity and pressure conditions at the inlet and outlet). The model created this way was transferred to Fluent program [6].

Fluent program is commonly used CFD software, which defines boundary conditions (Fig. 9) that are understood as a precondition for the correct calculation. The Turbulent model was as two – equations $k - \varepsilon$. This is the most widely tested and used a two-equation -transport- model (two transport equations for k and ε) [7].

The transport equations for k and ε can be deduced from the modeled equations by introducing a gradient diffusion hypothesis (with isotropic viscosity) in the turbulent diffusion terms for k and ε, and replacing R_{ij} in the production terms by its behavior law (1):

$$R_{ij} = \frac{2}{3}k\delta_{ij} - v_t\left(\overline{U}_{i,j} + \overline{U}_{j,i}\right), \tag{1}$$

$$\frac{dk}{dt} = P + \left(\frac{v_t}{h_k}k_{,i}\right)_{,i} - \varepsilon, \tag{2}$$

$$\frac{d\varepsilon}{dt} = C_{\varepsilon 1}\frac{p_\varepsilon}{k} + \left(\frac{v_t}{h_\varepsilon}\varepsilon_{,i}\right)_{,i} - C_{\varepsilon 2}\frac{\varepsilon^2}{k}, \tag{3}$$

With and $P = v_t\overline{U}_{i,j}(\overline{U}_{i,j} + \overline{U}_{j,i})$, $v_t = c\mu(k^2/\varepsilon)$, h_k and h_ε standing for turbulent Prandtl – Schmidt numbers assumed to be constant. The components of the Reynolds stress tensor are obtained from the behavior law $R_{ij} = 2/3k\delta_{ij} - v_t(\overline{U}_{i,j} + \overline{U}_{j,i})$. If this law gives a good approximation of the shear stresses, the normal stresses are, however, poorly estimated in general.

Determination of numerical constants
The decay of grid turbulence allows us to determine the value of constant $C_{\varepsilon 2}$; its value is found to be $C_{\varepsilon 2} = 1.9$.
Wall turbulence (logarithmic region of the turbulent boundary layer on a flat plate) yields the relation:

$$C_{\varepsilon 1} = C_{\varepsilon 2} - \frac{K^2}{h_\varepsilon\sqrt{c_\mu}} \quad (K = 0.41 \text{ Karman constant}) \tag{4}$$

and also $c\mu = u_*^4/k^2$ with $u_* = \sqrt{\tau_p/\rho}$ (wall friction velocity).

Referring to experimental data, it can be deduced $c\mu \approx 0.09$

The numerical values of constants recommended by Launder B.E., (LAU 75A) are the following:

$$c\mu = 0.09, \ h_k = 1.0, \ h_\varepsilon = 1.3, \ C_{\varepsilon 1} = 1.44, \ C_{\varepsilon 2} = 1.92 \quad (5)$$

The k–ε model generally gives good results in simple flows as far as the means of the velocities and energies are concerned. But it cannot predict sufficiently the specific characteristics of complex flows (a recirculation of the regions, the secondary flows, etc...) [8].
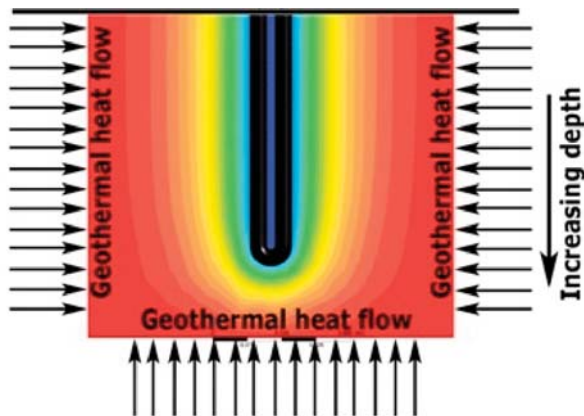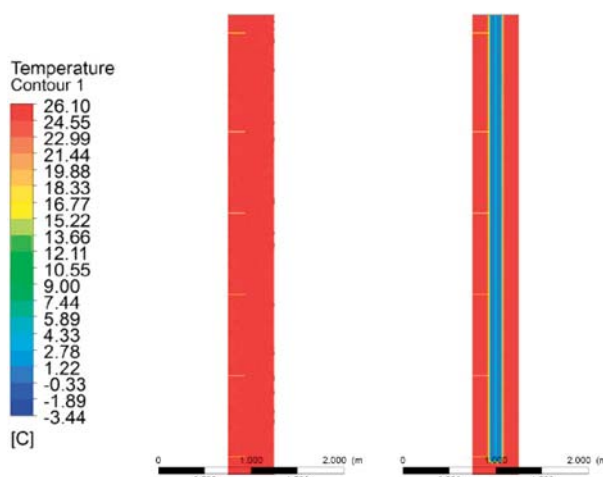

Fig. 9 Boundary conditions

*Fig. 10 Simulation begins
at 0 s*

*Fig. 11 Simulation
after 10 min*

Boundary conditions for simulation of heat transfer in geothermal borehole simulator were as follows:

- time for cooling soils,
- stabilization time for continual delivery of low potential heat energy.
- temperature of soil and ambient,
- physical properties of soil and pipe[9],
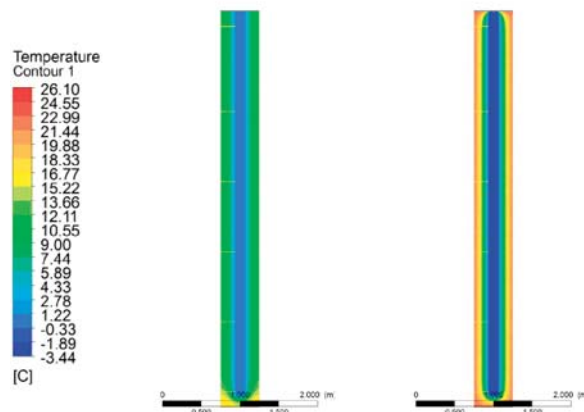- wall temperature of the pipe and setting the conductivity to extract low potential heat from soil [10] [11].

*Fig. 12 Simulation after
19 hours, stabilized*

*Fig. 13 Simulation
after 48 hours*

Results from the numerical simulation on one of the borehole models are shown in Figs. 10–14, where we can see when the simulation begins at the temperature 26.1 °C. Fig. 12 shows the result after accumulation that lasted 19 hours (borehole model was cooled to an average temperature of 11.4 °C by U-ground heat exchanger with a temperature −0.6 °C). Then the calculation was changed (turn on the heating shell borehole model at 22 °C and cooling by U-ground heat exchanger with a temperature −3.4 °C). This way a continual delivery of heat for the transfer of low potential heat energy from soil was provided. Fig. 13 presents the final result where the borehole model is stabilized. Figs. 10–14 show a yellow line marking the place where measurements taken on the borehole model were recorded.

The simulation results from each time step shown in Fis. 15 – 17 were gathered from the same point (location of the temperature sensors is shown in Fig. 3; measuring points are shown in Fig. 6; placement of temperature sensors in the simulations are yellow lines; the results are from the measuring positions T1 and T21) as taken on the borehole model. The results after 10 min of stimulation can be seen in Fig. 15. The temperatures taken in the first T1 and last T21 points have identical values. It means that the whole model has equally stabilizing temperature along the cross section.

Fig. 16 shows the simulation results after 19 hours where the cooling of the borehole can be seen.Temperatures measured in the first and last measurement points indicate that the average temperature reached in the borehole model was the same as the measured temperature.

Fig. 17 shows the simulation results after 48 hours where the temperatures in the first and last measuring point are uniform along the cross-section. It means that the same average temperatures were achieved as those taken on the simulator and the model was again stabilized. This will ensure a uniform heat delivery.
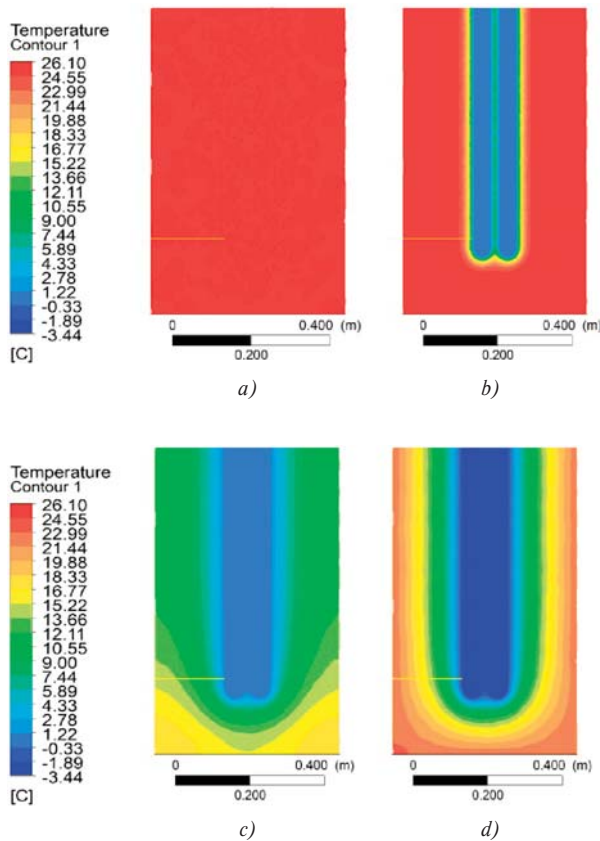

Fig. 16 Simulation result after 19 hours

Fig. 14 Results of individual simulation steps (a – 0 s, b – after 10 min., c – after 19 hrs and d – after 48 hrs)

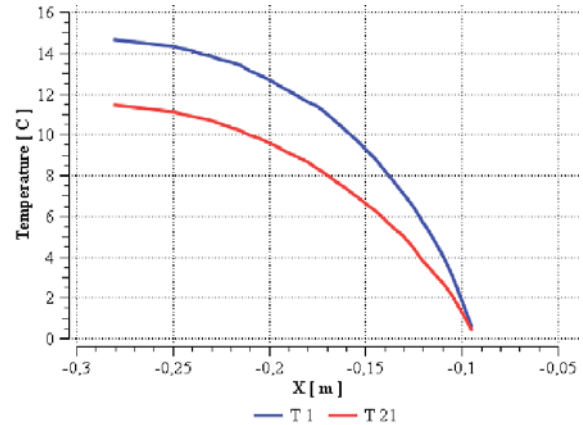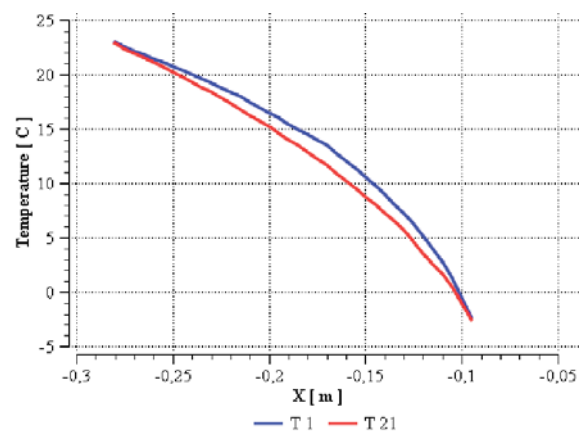*Fig. 17 Simulation result after 48 hours*

5. Discussion

The designed equipment (simulator) for heat transport enables a relevant comparison of the thermal power transmitted from the rock heat by means of the U-ground heat exchangers and by means of heat pipes with thermo-siphon effect under the same conditions. This problem cannot be solved in a classical borehole since rock characteristics differ from one borehole to another. The presented simulator is a suitable device for testing the heat potential of geothermal borehole. Based on the known parameters of the rock (thermal conductivity, capacity, rock moisture) it is possible to verify the measured heat outputs during the testing of the borehole potential (from the temperature and flow of tested fluid) and to find the dependence between the characteristic of borehole soil and their temperatures.

6. Conclusion

The paper describes the construction design, schemes and connection of the simulator geothermal borehole model located

Fig. 15 Simulation result after 10 min

in the laboratory, a creation of CFD model simulator and CFD simulation results of the model simulator in which the transfer of low potential geothermal energy was simulated. The CFD simulations results were compared with a real simulator. Comparison of simulation results showed that they are in good agreement with the results of measurements. The device for simulation of low potential geothermal heat allows to mimic the processes taking place in deep boreholes. Examining these processes in laboratory conditions allows getting some knowledge of a suitable heat carrier, soil conductivity, etc.

In laboratory conditions it is possible to achieve the carbon dioxide saturation point through changes is CO_2 pressure and temperature. If we are able to maintain this condition and simultaneously accumulate heat to the borehole, we can provide a long-term heat take away in the exchanger. In real conditions when the seasons change, this is not possible. Carbon dioxide as the working substance in heat tubes works without forced circulation and has the potential to be used in real boreholes.

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