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Polish Journal of Chemical Technology, 26, 2, 86—91, 10.2478/pjct-2024-0022

Experimental validation of a CFD model of a ground heat exchanger with slinky coils

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Rising energy prices have increased the popularity of many renewable energy sources including heat pumps. In the case of ground heat pumps research related to the analysis of the operation and selection of ground heat exchangers as a heat source are insufficient. With this in mind, on the operation of the horizontal slinky coil heat exchanger research work has been undertaken. As a research tool, the Computational Fluid Dynamics has been used. To check the adequacy of the CFD model, a validation of the model was carried out using the results of research on a real heat exchanger. Comparison was made: values of ground temperatures, outlet temperatures from the exchanger, and heat flux exchanged by the heat exchanger. In the opinion of the authors, the validation of the CFD model was successful.

Keywords: ground heat exchanger, CFD, experimental validation.

INTRODUCTION

In recent years, a systematic global increase in energy prices has been observed[1]. At the same time, information about the gradual depletion of fossil fuel deposits is becoming more and more frequent[2]. Energy policy is also heavily influenced by European legislation to reduce and even zero carbon emissions to combat climate change[3]. All these facts have resulted in increased popularity of renewable energy sources and increased scope of scientific research in this area. Therefore, more and more advanced technologies are being used to obtain cheaper energy with increasing capacities of installed renewable energy sources[4]. However, these installations are often not carried out in accordance with scientific and technical thought. An analysis of their operating conditions is not carried out or even goes against these conditions. Such actions result in poor quality of emerging installations and inflated investment and operating costs[5]. It appears that more research is needed into the proper construction and operation of emerging installations.

Among the devices suitable for obtaining renewable energy, heat pumps stand out. They are relatively cheap, easy to install and operate. In Poland, their popularity has been growing steadily over the last twenty years[6]. The theory behind heat pumps is relatively well-known. Several methods have been developed for sizing heat pumps and predicting their efficiency under given operating conditions. However, these studies have been particularly concerned with air-water heat pumps[7]. The situation is slightly different in the case of ground heat pumps. It is known that the operation of such a pump is significantly affected by the type and configuration of the ground heat exchanger, which is the source of heat for the heating system. The work of such exchangers, their performance, the behaviour of the soil around the exchanger pipes, and the influence of atmospheric conditions are closely related. Research in this area is still insufficient. This applies in particular to the modeling of the operation of such an installation and, based on the results of the simulation, the design and selection of the actual operating parameters.

As a lower heat source for ground heat pumps, in practice one of the three most popular types of ground heat exchangers is used. These include linear horizontal exchangers, spiral horizontal exchangers (slinky), and vertical exchangers. Of these, slinky spiral exchangers are becoming increasingly popular. This popularity is due, among other things, to their compact design compared to linear exchangers, which results in a reduced installation area and lower investment costs in relation to vertical exchangers[8].

Despite the increasing applications of the horizontal spiral heat exchanger as a bottom heat source, its research is not very advanced. One mathematical model describing the operation of an exchanger of this type has been developed so far[9]. Experimental studies of slinky exchangers have mainly been conducted at laboratory scale[10, 11]. Few studies conducted in real-scale installations have been published[12–15]. Although these studies have provided insight into a number of properties of slinky spiral exchangers, they are not complete and need to be continued.

In the opinion of the authors, there is a need to conduct research that could allow to determine guidelines for the selection of spiral exchangers. It seems that a good tool for achieving this goal is the use of computational fluid dynamics (CFD) tools. However, for the CFD model to be adequate, its validation should be carried out by checking the results of simulation calculations with the results of the actual heat exchanger. An attempt at such validation is described in this paper.

MATERIALS AND METHODS

Field Research

To obtain experimental data that could be used to validate the CFD model, a field research stand has been designed and built. The test site was located in the municipality of Jordanów in the Malopolskie Voivodeship. A schematic diagram of the stand is presented in

The heat exchanger consisted of one 1 m diameter loop and was made of 0.032 m diameter PE pipe. The exchanger loop was installed in the ground at a depth of 0.5 m. The depth of installation of the exchanger has been selected so that the impact of the temperature of the ground surface can be observed. To measure the ground temperature, four DS18B20 temperature sensor

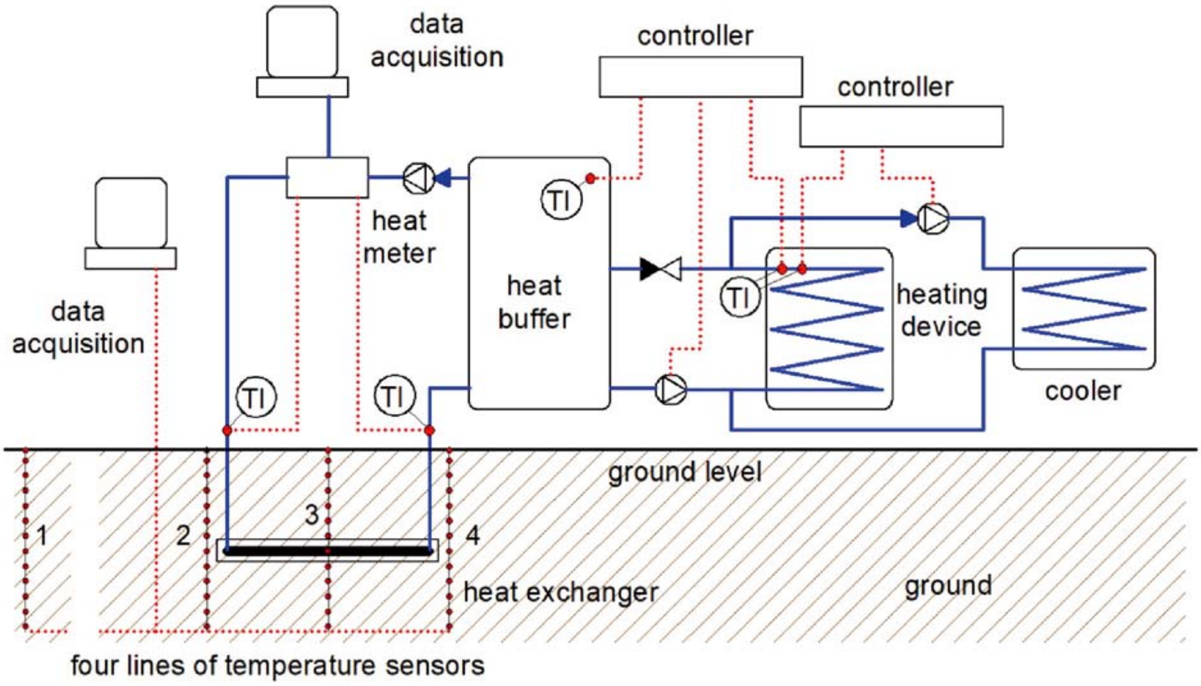

Figure 1. Schematic diagram of the stand

lines of 13 sensors per line were installed from a depth of 1 m to the ground surface. One line in the axis of the exchanger (No.3), two at opposite pipe sections (Nos.2 and 4), and one at a distance of 4.5 m from the exchanger (No.1). These lines provided an unobstructed ground temperature reading. The installed exchanger was operated in ground heating mode. Admittedly, under typical operating conditions, the ground heat exchanger is the lower heat source for a liquid-to-liquid heat pump. However, it is also possible to reverse the work, i.e. regeneration of the ground after winter or transfer of heat to the ground during the use of the installation with a heat pump for air-conditioning purposes. Then the ground is heated by liquid supplied, e.g. from heat pumps working with the so-called reverse circulation, air conditioning devices, etc. This situation is easier to simulate in field conditions because it does not require a heat pump connection. It is only necessary to install a heat source, such as a boiler or other heater. On the model side, the difference lies in changing the operating conditions in such a way as to obtain the right direction of heat movement from the heat exchanger to the ground. The principle of operation of the heating and measuring system was as follows. The working medium of the ground heat exchanger was water. The heating device was a boiler equipped with a control system. The boiler heated the water in the heat buffer. In the event of overheating of the boiler, the controller turned off the fan that pumped air to the boiler furnace. Full heat of the heat buffer took about 3.5 hours. The temperature set in the heat buffer was 55 °C and was maintained to an accuracy of 0.5 °C.

A circulation pump on the side of the slinky ground heat exchanger has been installed. It pumped the working medium through the flow meter and the ground exchanger. Water at a temperature of approximately 55 °C heated the ground around the exchanger and returned to the buffer. Two temperature sensors integrated into the heat meter were placed on the inlet and outlet of the heating medium from the heat exchanger.

The workflow of the research was as follows. Prior to the experiment, the necessary installation and test works were carried out. Five days were then waited to establish the temperature in the ground disturbed during the installation work. The tests were carried out between 05.12.2017 and 07.12.2017. The experience consisted of continuous heating of the ground with water at a temperature of 55 °C for 72 hours. During this process, the following process parameters were measured:

– temperature in the ground by 48 sensors and temperature on the ground surface by 4 sensors,

– temperature changes at the inlet and outlet of the exchanger,

– mass flux of the liquid flowing through the exchanger.

CFD SIMULATION

CFD simulation was performed for a 3D model reflecting the actual ground heat exchanger surrounded by the ground model (Fig. 2). Simulation calculations were performed in CFX Flow, part of the Ansys package.

The material assigned for the heat exchanger tube was PE with parameters ϱ = 1200 kg/m^3 and c_p = 2.3027 J/(kgK). The heat exchanger tube wall was defined as a *thin material* with the thickness of the actual heat exchanger tube, i.e. 2 mm. The soil model has been defined as a so-called *continuous solid* with the *Heat Transfer – Thermal Energy* option, which is required for the simulation of transient processes. Water was adopted as the working medium in the exchanger – *continuous fluid* with the option *Heat Transfer – Thermal Energy Model*. A *k-epsilon* model was adopted to describe the turbulent flow. The walls of the vertical tube sections of the exchanger were defined as adiabatic baffles. The horizontal section of the exchanger, which was the heat exchange surface with the ground, has been defined as a *fluid – solid* with *Heat Transfer – Conservative Heat*

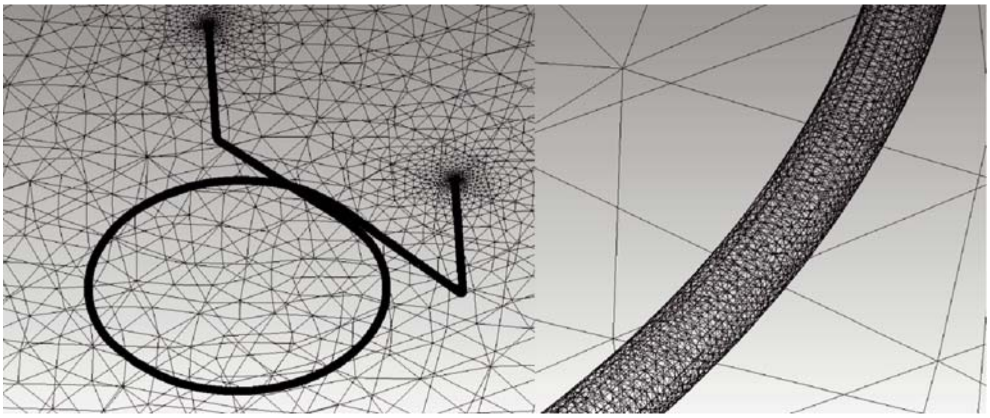

Figure 2. Calculation mesh of the researched heat exchanger

option. The detailed equations of the mathematical model used in the CFX module of Ansys to solve the formulated problem are available in publication[16]. The Coupled Solver for the finite element method which is implemented in the CFX package has been used as the solution method. A description of this method is also included in publication[16].

Data from field measurements were used as initial and boundary conditions. The initial conditions were the initial temperature of the ground. The boundary conditions included: the temperature of the ground surface, the temperature, and the volumetric flow of the water supplying the exchanger. The simulation duration was set at 72 hours. Results were archived every 15 minutes.

RESULTS AND DISCUSSION

As already mentioned, the process of heating the ground lasted continuously for 72 hours. During the measurements, snow fell on the area where the heat exchanger was installed. The snow cover was not uniform all the time. At the beginning of the process, the snow was lying above all the measuring lines and only above line 2 for about 2000 minutes. The graphs in Fig. 3 show the temperature changes for sensors located on the ground surface.

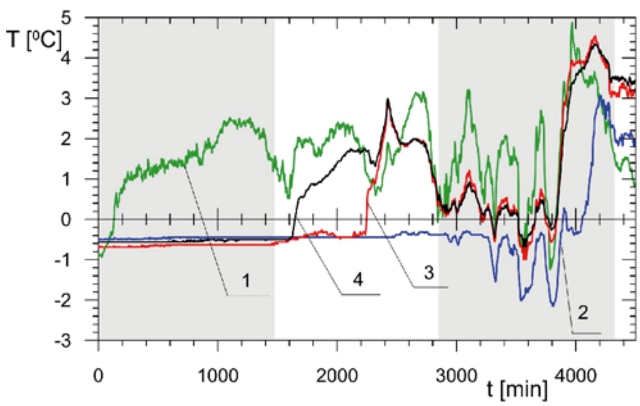

Figure 3. Temperature profiles on the ground surface during the experiment

An insulating effect of the snow cover during the first day can be observed. Namely, no diurnal cycle of temperature changes was observed here. On the other hand, once the snow layer has melted over lines 1, 3, and 4, on the second and third days of the experiment, the diurnal cycle is clearly marked.

The results of measurements of temperature changes in the ground, together with the results of CFD simulations, are presented in the graphs (Fig. 4).

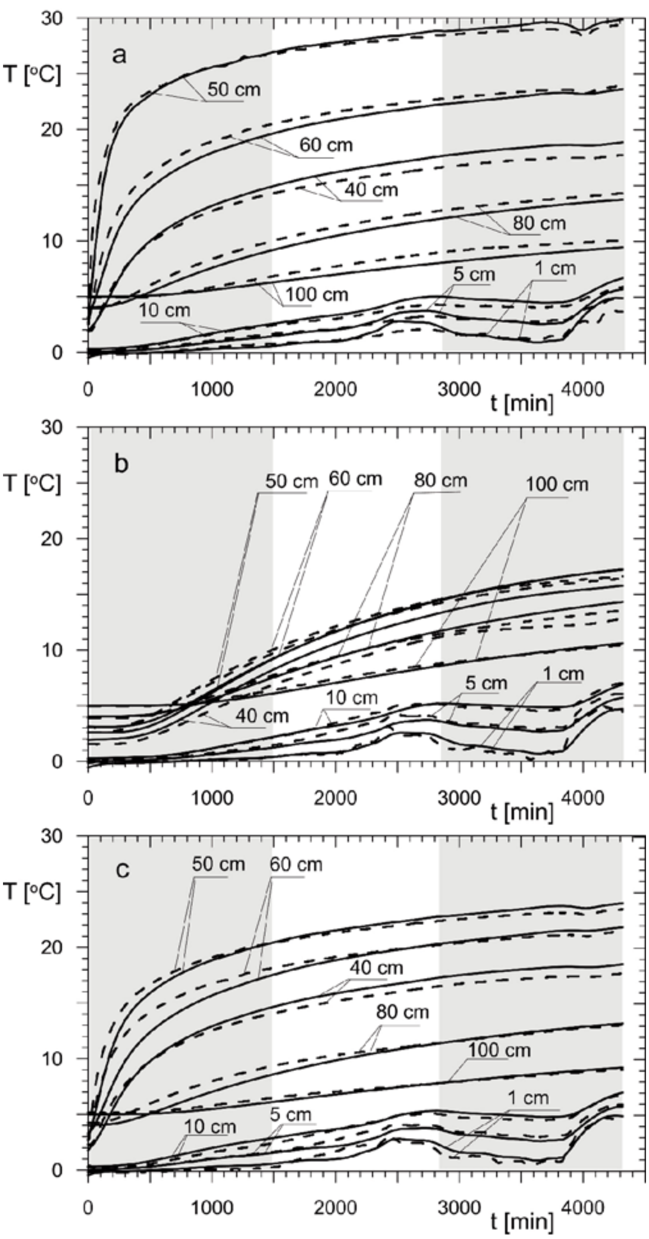

Figure 4. Comparison of ground temperature profiles measured by measurement line sensors (_ _ _) and determined during CFD simulation (___) at different depths; a – line 2, b – line 3; c – line 4; the gray color indicates the subsequent days of measurements

The comparison of the results showed good quantitative consistency. The results obtained from the CFD simulation coincide with the temperatures measured in the ground. In addition, you can observe the mapping by CFD simulations of several phenomena that took place during the experiments on the real exchanger. As can be seen, during the measurements, an emergency situation occurred around 3500–4000 min of the process. The water supply system has been air-locked, the water flow has been blocked, and there has been a temporary decrease in the amount of heat supplied to the ground. In all diagrams, this situation is illustrated as a drop in temperature recorded at this time by sensors installed near the exchanger pipes and above and below the exchanger level. This situation was also mapped in CFD simulation. The phenomena on the ground surface and their impact on the temperature at the surface were also mapped.

The differences in ground temperature change over time, obtained experimentally and through CFD simulations, are no greater than 2 °C. These discrepancies were caused by inaccuracies in the installation of the sensors on the ground, the length of the measuring elements (50 mm), and also simplifications in the CFD model. The soil model used did not take into account the impact of groundwater and the migration of moisture, heterogeneity, and partial drying during excavation.

Analysing the following graphs (Fig. 5) showing the temperature profiles following the ground depth for selected process times, it can be seen that the highest ground temperature gradients are observed for sensors placed in the plane of the exchanger in lines 2 and 4, i.e. in lines placed close to the exchanger pipe. Observation of the results of line 3, installed in the axis of the exchanger, showed that during the initial heating period the ground temperature practically does not change. Only after a time of about 600 min, when the heat front reaches the axis of the exchanger, does the ground temperature change.

In addition, similar profiles for measuring line 1 have been provided (Fig. 5d). As can be seen, the temperature of the ground at a distance from the exchanger was not disturbed during the experiment.

The data on the inlet and outlet temperatures from the exchanger and on the flow of the working liquid were determined based on the readings of the CQM III heat meter integrated with the LQM – III flow meter. The flow rate of water circulating in the ground heat exchanger and the temperature changes at the inlet and outlet of the heat exchanger are shown in Fig. 6.

Two failure incidents can be observed on the graph. The first during the initial heating period, between 0–250 minutes, and the second between 3600–4100 minutes of the process. Significant spikes in the working liquid flow were observed at this time, due to the system being air-locked. Disturbances during the final period of the experiment were also observed in the temperature diagrams on the ground and at the inlet and outlet of the working liquid.

A comparison of the measured and obtained from the simulation temperature at the outlet of the exchanger is given in Fig. 7.

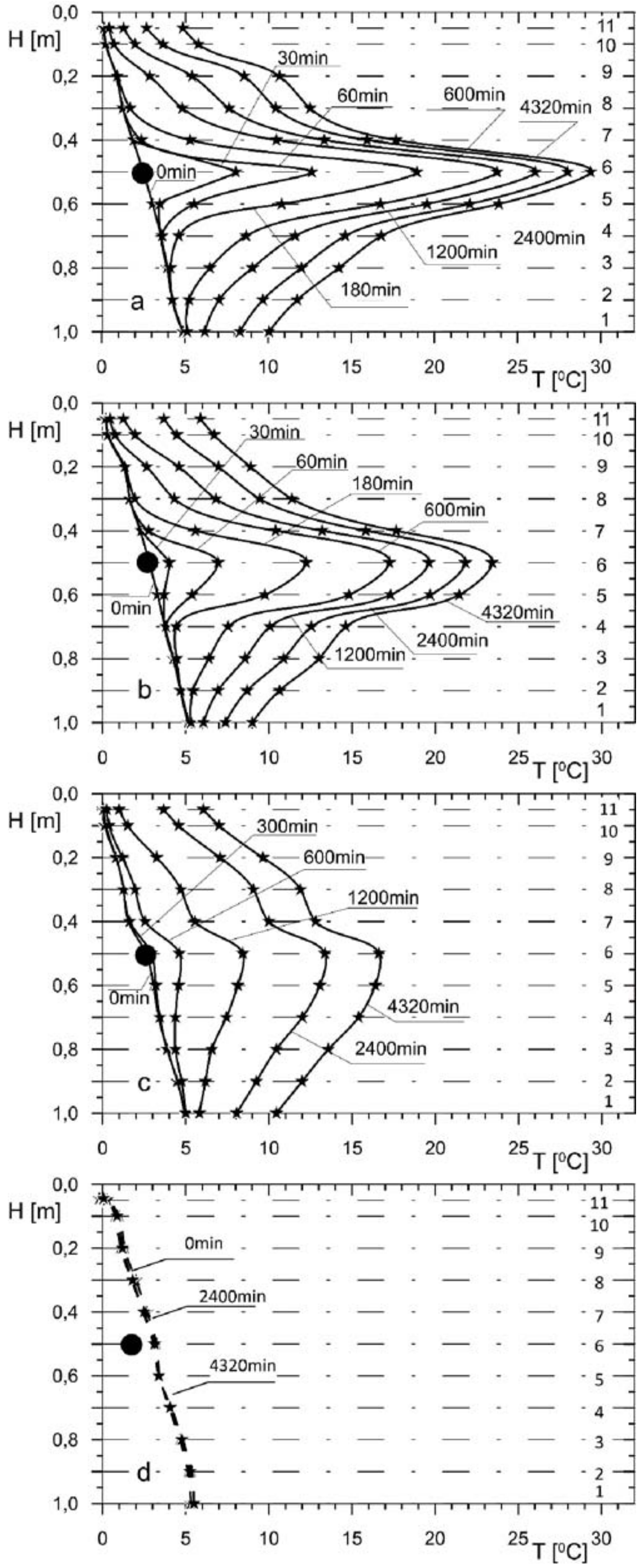

Figure 5. Profiles of ground temperatures at the different depths for selected moments of the experiment duration recorded by the sensors of the measuring lines; a – line 2, b – line 3; c – line 4; d – line 1; dot marks heat exchanger; stars and (_ . _) marks temperature sensors; 1 – 11 numbers of sensors

The slinky exchanger outlet temperature values obtained from the CFD model solutions have a very good agreement with the results obtained from the measurements. The maximum temperature difference between these values was 0.1 °C on average.

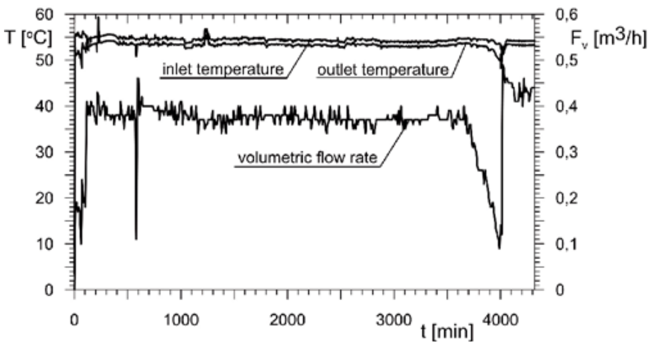

Figure 6. Results of measurements of the temperature of the working liquid at the inlet and outlet of the heat exchanger and its flow rate

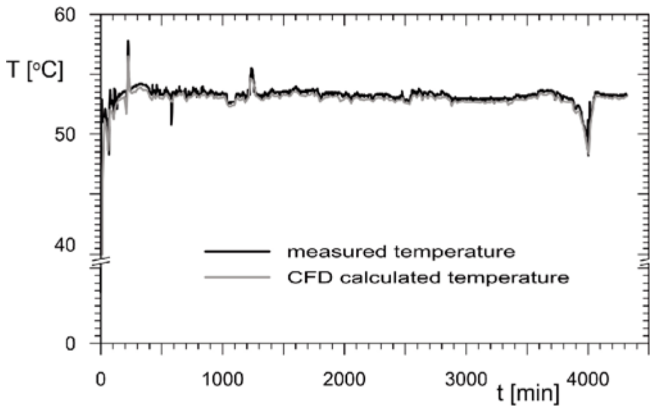

Figure 7. Comparison of the temperature of the medium at the outlet of the heat exchanger

It can therefore be concluded that CFD simulation, using real initial and boundary conditions, predicts changes in the temperature of the working medium at the outlet of the exchanger with very good accuracy. This is of particular importance for modeling the operation of designed exchangers.

The amount of heat delivered to the ground was calculated according to the formula (1):

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_{in} - T_{out}) \quad (1)$$

where: – heat flux, – mass flow rate of the working medium, – specific heat of the working medium, – heat exchanger inlet and outlet temperatures.

The values of heat delivered to the ground determined using the formula (1) for the experimental data were compared with the results obtained from the simulation (Fig. 8).

It can be said that in the initial phase of heating the ground the heat flux was the largest and was about 1650 W, while in the following hours, it decreased to the level of about 450–550 W. This phenomenon is associated with a decrease in the temperature difference and therefore a decrease in the driving force of heat transfer. For a time of 300–500 minutes of the process, the heat flux graph is flattened, which can be explained by the fact that the heat flux began to reach the axis of the exchanger (r = 0 m). As a result, the temperature difference between the axis of the exchanger and the wall of its tube began to decrease, so that the heat movement in the horizontal direction from the wall of the exchanger tube to its axis lost its intensity. Fluctuations in the heat flux released to the ground were due to the variable flow

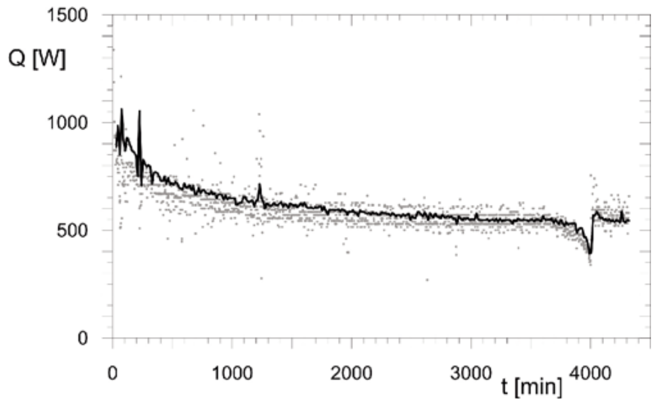

Figure 8. Energy delivered to the ground - comparison of results from measurements and CFD simulations

of liquid flowing through the exchanger and the variable supply temperature of the exchanger (Fig. 6). Apart from the incident around 3800–4000 minutes, it can be seen that the heat flux is moving toward a steady state. The duration of the experiment, which is 72 hours, is too short a period to achieve it.

This graph also shows that CFD modeling can accurately reproduce the average heat flux that a slinky exchanger exchanges with the ground.

CONCLUSION

Summarizing the comparisons presented between the results of the field experiments using the actual heat exchanger and the results of the CFD simulations, the following conclusions can be drawn:

– using CFD modelling it is possible to realistically represent the conditions and performance of a ground heat exchanger,

– CFD modeling makes it possible to analyse the transient operation of a ground heat exchanger,

– using CFD, it is possible to determine temperature values at any point in the ground geometry, which can be used to analyse exchanger operating conditions under adverse conditions, extreme and emergency situations, and in design activities,

The results of CFD simulations make it possible to determine changes in the thermal power supplied to or extracted from the ground during the operation of the exchanger and can provide information about the temperature of the fluid circulating in the exchanger, which is of particular importance in assessing the momentary Coefficient of Performance (COP).

In the authors' opinion, the validation of the CFD model with experimental results using an actual heat exchanger was successful, so the conclusions can be extended. CFD modeling and simulation can be used to design slinky ground heat exchangers not only for a single loop, but also for more complex arrangements including multi-row heat exchangers. This makes it possible to predict the performance of the designed exchangers in the short and long-term. It also makes it possible to determine the temperatures of the working liquid at any point in the geometry, which is particularly important for determining the performance of the heat pump. CFD modeling can be used to optimise the heat exchanger at the design stage and during its operation. It is also possible to study the influence of atmospheric conditions on the operation and efficiency of the entire system.

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