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Studies on the Field Type Ground Heat Exchanger Coupled with the Compressor Heat Pump (Part 1)

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1. Introduction

This paper focuses on the CFD analysis of the vertical FGHE and its influence on the compressor heat pump performance. The numerical research were carried out for the FGHE varying geometry and ground's temperature boundary conditions. However, the primary aim was to improve the quasi-steady heat pump operation modelling.

In the engineering practice, it is common that the heat flux transferred to the heat pump's evaporator from the low heat source is being averaged with respect to the FGHE work time. On the other hand, it is well known that the heat flux value, varies in time, due to the soil and the ground heat exchanger external wall temperature variation.

In the cases having been analysed during numerical research, of which, the results are presented in the work, two FGHE's lengths were taken into account. Moreover, two different epsilon values were considered (Fig.1 and Fig.2).

There has been done a numerical analysis of 170 hours of continuous work (Dolna, 2016). The present work concentrates on the FGHE-compressor heat pump coupling.

2. Computaitonal model description and boundary conditios

The reference FGHE consisted of two 110 meters long coaxial pipes. The external one had an oval bottom. The FGHE was hooked in the ground, which was divided into three layers, of different thermophysical properties. As a comparative case, 27.5 meters long FGHE surrounded by the soil of one type was examined. Fig.3 illustrates the outline of a computational domain.

In the calculations, there was taken into account the finite volume of the ground, simulating infinite half-space. The initial temperature profile of the ground, in the numerical computations, in the UDF (User Defined Function) was defined and it is easy to modify. The numerical simulation calculations of the described FGHE have been done using the commercial software.

Boundary conditions and implemented UDF are as follows:

- the temperature variation with depth was given in User's Defined Function (UDF) and interpreted in Fluent as a temperature boundary condition on the outline of the whole computational domain
- the temperature profile was defined by the conjunction of two linear functions as the ground's temperature increase varies with depth
- the soil types
  - gravel – from 0 level to the depth of 20 meters:
  - clay – at depth range of (20-110) meters:
  - limestones – under 110 meters:
- inlet fluid temperature (3[ºC]) and inlet fluid pressure (10[bar])
- working medium – ethylene glycol
- ground surface temperature (marked in green in Fig. 3) was set at 6[ºC] or -2 [ºC]

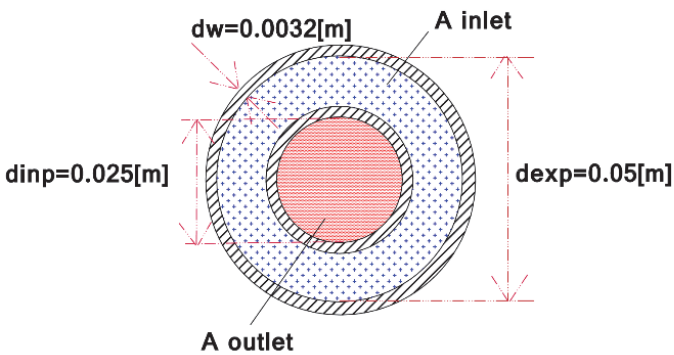

Fig. 1. Reference FGHE, $\varepsilon = 0.41$ (Dolna, 2016)
Rys. 1. Referencyjny GWCF, $\varepsilon = 0.41$ (Dolna, 2016)

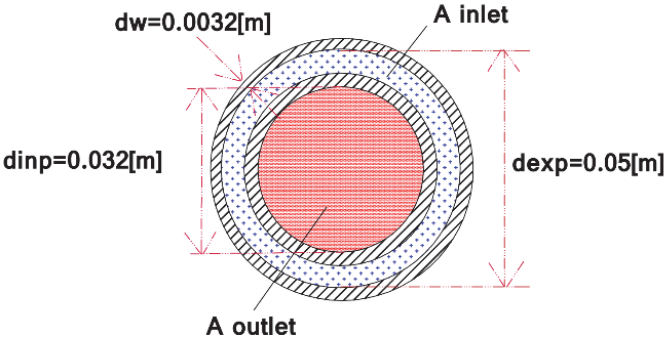

Fig. 2. Comparative FGHE, $\varepsilon = 1$ (Dolna, 2016)
Rys. 2. Porównawczy GWCF, $\varepsilon = 1$ (Dolna, 2016)

where: $\varepsilon = \frac{A_{outlet}}{A_{inlet}}$

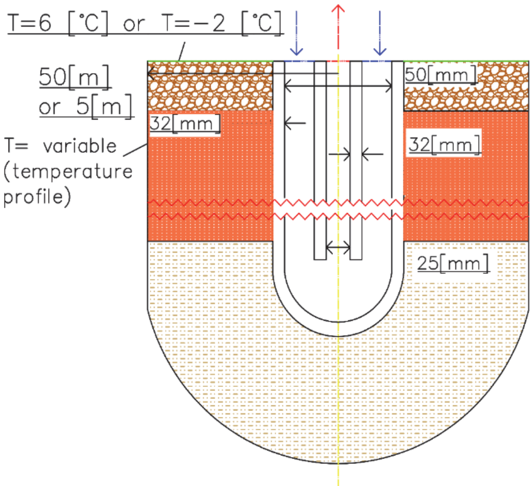

Fig. 3. Two-dimensional outline of the computational domain (Dolna, 2016)
Rys. 3. Dwuwymiarowy szkic domeny obliczeniowej (Dolna, 2016)

The FVM was used to discretise the computational domain. For the purpose of numerical calculations, the structural mesh was generated. Obviously, the mesh size varied according to the FGHE's length. The mesh influence was not discussed in the current paper however described problem is mesh independent as the proper analysis was caried out.

3. Conjunction of 0D-level (compressor heat pump cycle) and 3D-level (CFD FGHE) programming

In this section, there is described the conjunction of the compressor heat pump cycle author's programme with the CFD analysis results of the FGHEs of different lengths and outlet/inlet surface ratios. As a result of 0D-3D level programming, there was created a computational model, which provides the possibility of the heat pump system designing in a way, which hasn't been used before. Further work on this author's software development may result in creating a commercial programme, which could be widely used by the heat pump systems designers.

The numerical research, of which the results are discussed in this subsection, confirm the time dependent FGHE heat-flow parameters variation, what in conjunction with the geometry variation, influences the compressor heat pump work. According to the above, the 0D-3D programming conjunction is about the CFD (3D) analysis results implementation into author's code *COMPRESSOR HEAT PUMP* (0D). The FGHE varying heat-flow parameters are as follows, the mass flow rate and the temperature, and the heat flux transferred from the surrounding ground. The FGHE length variation results in the mass flow rate change. Consequently, the FGHE working fluid outlet temperature and the heat flux also change.

The FGHE outlet is identical with the GCHP evaporator's inlet. The FGHE working medium outlet temperature variation corresponds with the GCHP evaporator's heat flux value change. As the FGHE is coupled with the compressor heat pump, its factual influence should be taken into account. However, nowadays, for instance the FGHE outlet heat flux is mostly being averaged. The present work shows the importance of a quasi-steady GCHP system modelling as the FGHE outlet heat flux value decreases with the work time significantly.

This work concerns also the analysis of a case of a heat pump heating power decrease. It is obvious that the heating or cooling devices do not work with their nominal power all the time. Bearing on mind this fact, FGHE work under varying load was studied. Figure (Fig.4) presents heat characteristics of FGHE of different mass flow rate and corresponding heat pump heating power.

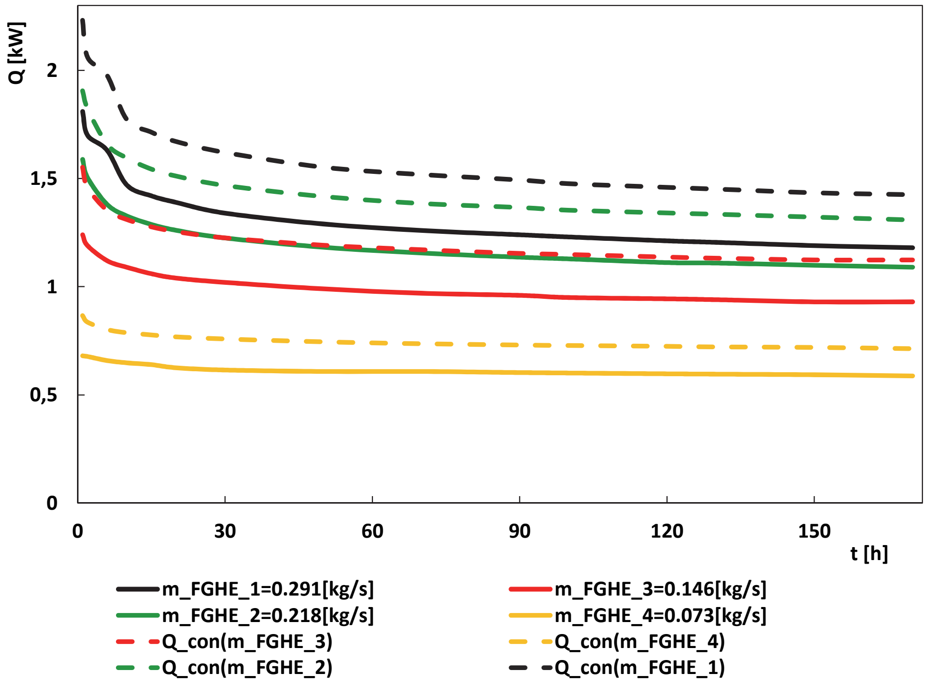

Fig. 4. Variation of the heat pump heating power resulting from the FGHE heat load variation during continuous quasi-steady work (Dolna, 2016)
Rys. 4. Zależność mocy grzewczej sprężarkowej pompy ciepła od zmiennego obciążenia GWCF (Dolna, 2016)

Continuous lines correspond to FGHE varying load, while the intermittent ones correspond to the varying heat pump heating power. For the cases of the FGHE, working under varying load, the COP value of the compressor heat pump was computed and is exposed in the figure attached below (Fig. 5). On the basis of this analysis having been carried out, it is now possible to estimate how will the FGHE work if the GCHP heating power decreases.

For the purpose of the FGHE-HP coupling, one hundred and seventy hours of continuous FGHE work had been analysed. Figure 6 and 7 visualise the results of FGHE-CHP conjunction reached through the 0D-3D level programming linkage.

On the basis of these studies it become possible to model quasi-steady heat pump's work.

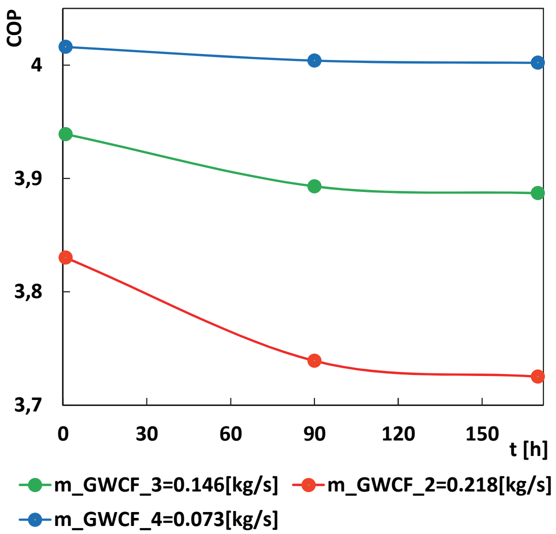

Fig. 5. Heat pump COP variation with FGHE load during quasi-steady continuous work (Dolna, 2016)
Rys. 5. Wahania wartości COP sprężarkowej pompy ciepła w czasie ciągłej quasi-stacjonarnej pracy, wynikające ze zmiany obciążenie GWCF (Dolna, 2016)

Figures exposed in the work (Figures 4-8) visualise the results received on the basis of the 0D and the 3D programming conjunction. The black continuous line (Fig. 6) refers to the FGHE reference model of the mass flow rate equal $\dot{m} = 0.291 \left[\frac{kg}{s}\right]$. The heat pump working medium used in these particular computations was R600a, however, the author's software provides the use of 13 different refrigerants, however the list of working fluids may be defined in any other way regarding user's needs.

The results presented in Fig. 5 concern the HP COP value variation with the FGHE circulating pump electric power, being dependent of the FGHE mass flow rate. Moreover, from the figure 6 it might be seen how does the COP value vary in time during the continuous 170 [h] work. The heat pump coefficient of performance value, was calculated on two ways, using author's code. First approach did not include the amount of the electric power having been consumed by the low heat source heat exchange system circulating pump. In the second approach, the FGHE circulating pump electric power was taken into account. However, from the realistic point of view, the electric power of the circulating pumps of the low and high heat pump source should be taken into account when computing the COP value. The aim of the current analysis is to show the difference between the COP value having been computed in two different ways, described above. The results are as follows: $COP_1 = 4.081 -$ the value of the heat pump COP computed without taking into account the electrical power of the low heat source circulating pump. $COP_2 = 3.323$ corresponds to the latter algorithm, which included the low heat source system (in this case it is the LFGHE) circulating pump electric power.

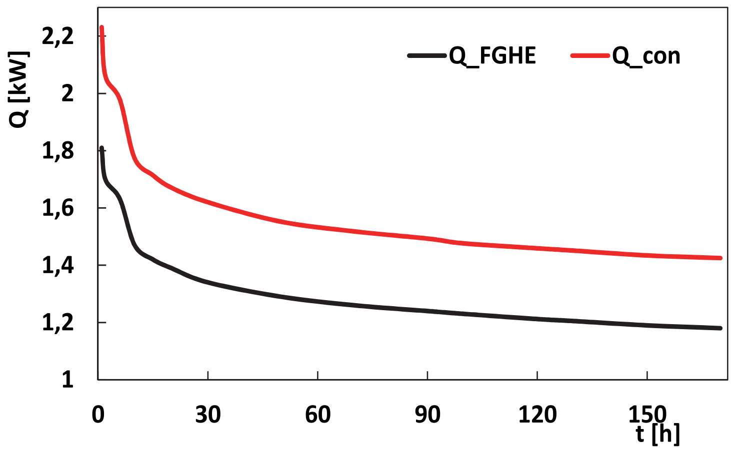

Fig. 6. Q_FGHE – time dependent thermal power of the FGHE; Q_con – time dependent heating power of the compressor heat pump (Dolna, 2016)
Rys. 6. Q_FGHE – moc cieplna GWCF zależna od czasu; Q_con – moc grzewcza sprężarkowej pompy ciepła zależna od czasu (Dolna, 2016)

The computations have been done in terms of a non-stationary analysis. Moreover, the computations have run in the transient mode from the very beginning. It means that, the simulations did not start from the steady state and then have turn into a transient mode. It was noticed, that when the steady state computations run, the computational tool (Fluent) predicts the solution (which may not be the correct one) and when it is turned into transient mode, the results are not that satisfactory as they should be. This is the main and only reason why the transient mode should be switched on from the very beginning. The disadvantage of such a way of solving the problem is that it takes much more time, but the results are of a much better quality than in the case of steady – transient transition.

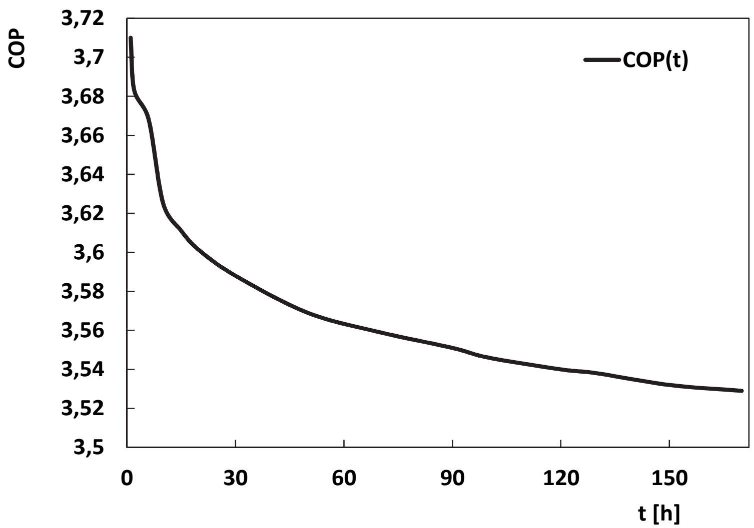

Fig. 7. Compressor heat pump COP value change during the quasi-steady 170 [h] continuous work (Dolna, 2016)
Rys. 7. Zależność wartości COP sprężarkowej pompy ciepła podczas 170 godzinnej quasi-stacjonarnej pracy (Dolna, 2016)

Characteristics presented in the following graph (Fig. 8) show the difference between one LFGHE and a set of four SFGHEs. The comparative criterion was the circulating power of the FGHE working medium as it is exposed in the table attached below (Table 1). From energetic point of view, one LFGHE is more efficient than four SFGHEs. However, sometimes environmental conditions unfavourable and it is not possible to drill as deep as 110 meters. From the graph (Fig. 8), we may see how much energy is being lost if the set of SFGHEs is applied instead of LFGHE.

Table 1. Juxtaposition of the comparative parameter values corresponding to a particular FGHE system (Dolna, 2016)
Tabela 1. Zestawienie wartości parametrów stanowiących kryterium porównawcze GWCF o różnej długości (Dolna, 2016)

Length [m]	Circulating power [W]
$L_{LFGHE} = 110$	26
$L_{SFGHE} = 27.5$	6 4 x 6= 24

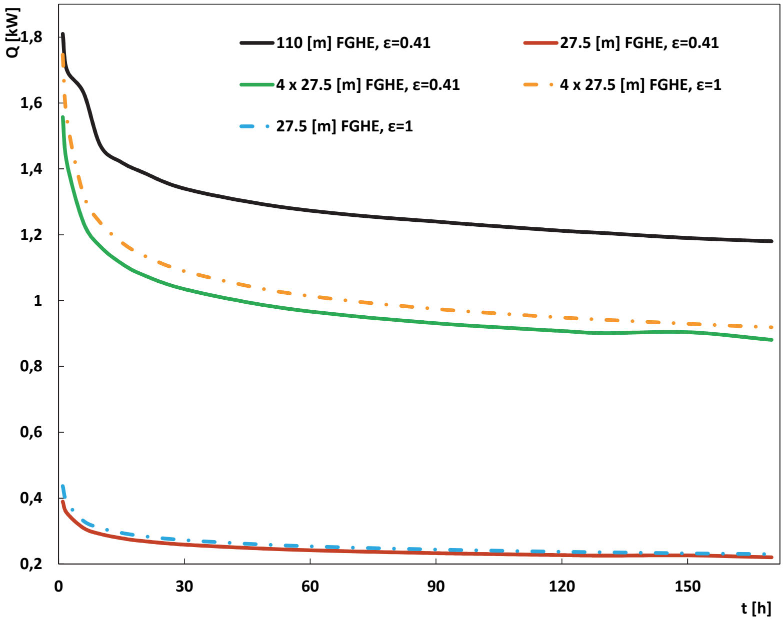

Fig. 8. Comparison of FGHEs of different length and time dependent epsilon values (Dolna, 2016)
Rys. 8. Porównanie GWCF o różnej długości i wartości współczynnika epsilon zależnego od czasu (Dolna, 2016)

Bearing on mind the need to consider whether the ground's surface (marked in green, in Fig. 3.) temperature strongly influence the borehole heat transfer or not, there was studied a case of a negative temperature value. Figure 9. presents the results of the analysis mentioned above, so it can be noticed that the temperature decrease at this particular surface did not influence the borehole heat transfer.

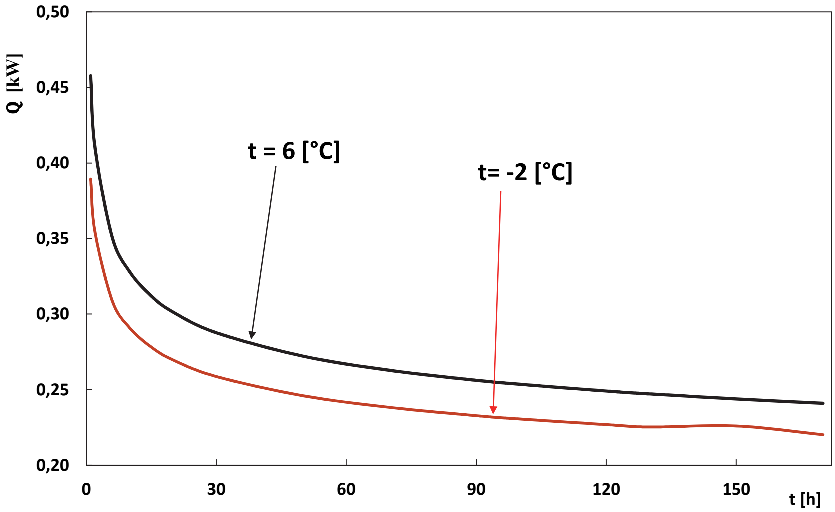

Fig. 9. FGHE time dependent thermal power for varying ground's surface tempearture boundary conditions (Dolna, 2016)
Rys. 9. Strumień ciepła, zależny od czasu, pozyskany przez GWCF dla zmiennych temperaturowych warunków brzegowych (Dolna, 2016)

4. Summary

On the basis of the results presented in the work, some assumptions were stated. First of all, the results confirm the thesis about the low heat source's (the ground) thermal efficiency depletion in time. It can be noticed in the graphs: Fig. 9, Fig. 8, Fig. 6 and Fig.4 that the thermal borehole power decrease in time significant. The quasi-steady character of the FGHE work should be taken into account in the GCHP system designing level as it was proven that the heat pump heating power varies in time. The latter is a result of not stable in time FGHE output heat flux. 0D-3D level programming coupling provided a computational tool to investigate the FGHE influence on the compressor heat pump and the quasi-steady CHP work could have been modelled.

Numerical research having been done, resulted in determining the FGHE performance working under varying load. For instance, 25 % reduction of the LFGHE mass flow rate resulted in 15 % decrease of the compressor heat pump heating power.

It was also noticed that, from energetic point of view, it is more efficient, to drill longer borehole instead of a set of short ones.

Nomenclature

FGHE – Field type ground heat exchanger,
CFD – computational fluid dynamics,
LFGHE – long FGHE (110 [m]),
SFGHE – short FGHE (27.5 [m]),
GCHP – ground coupled compressor heat pump,
GWCF – Field type ground heat exchanger (in Polish: gruntowy wymiennik ciepła typu Field'a),
HP – heat pump,
CHP – compressor heat pump,
COP – coefficient of performance,
FVM – Finite Volumes Method,
0D – zero-dimensional,
3D – three-dimensional,
$c_p \left[\frac{J}{kg\,K}\right]$ – specific heat,
$\dot{L}_{FGHE}[W]$ – FHGE circulating power,
$\dot{m} \left[\frac{kg}{s}\right]$ – FGHE working fluid mass flow rate,
$t_{out}[°C]$ – FGHE working medium outlet temperature, which is identical to the GCHP evaporator's inlet,
$A\ [m^2]$ – inlet/outlet surface of the FGHE.

Greek symbols

$\boldsymbol{\varepsilon} = \frac{\boldsymbol{A_{outlet}}}{\boldsymbol{A_{inlet}}}$ – epsilon – inlet/outlet surface ratio,
$\lambda \left[\frac{W}{m\,K}\right]$ – thermal conductivity,
$\varrho \left[\frac{kg}{m^3}\right]$ – density.

Subscripts

con – condenser.

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Badania gruntowego wymiennika ciepła typu Field'a współpracującego ze sprężarkową pompą ciepła (część 1)

Streszczenie

Niniejsza praca dotyczy analizy CFD gruntowgo wymiennika ciepła typu Field'a oraz zbadania wpływu jego pracy na działanie sprężarkowej pompy ciepła. W pracy podjęto problem gruntowego pionowego wspólosiowego wymiennika ciepła, ponieważ zdecydowana część prac naukowo-bawdawczych poświęcona jest wymiennikom gruntowym typu U-rura (Yang et al., 2010). Wobec powyższego, brak jest w literaturze cieplno-przepływowych charakterystyk gruntowego wymiennika ciepła typu Fielda. W pracy przedstawiono analizę quasi-stacjonarnej pracy gruntowej sprężarkowej pompy ciepła, co było możliwe dzięki sprzęgnięciu programowania na poziomie 0D i 3D. Praca całego systemu miała charakter ciągły i trwała 170 godzin. Sprężarkowa gruntowa pompa ciepła może pokryć zapotrzebowanie na ciepło pracując nawet w obiegu monowalentnym, ale system wymiany ciepła dolnego źródła ciepła musi być prawidłowo zaprojektowany. Ponadto, należy starannie dobrać właściwy pod względem efektywności czynnik roboczy sprężarkowej pomy ciepła (Bohdal i in., 2015). Obliczenia CFD zostały przeprowadzone przy użyciu komercyjnego oprogramowania. Natomiast, obliczenia obiegu sprężarkowej pomy ciepła zostały wykonane przy użyciu autorskiego programu. Przeanalizowano pracę GWCF o zdywersyfikowanej geometrii w trybie pracy nieprzerywanej. Zaimplementowano zmienne temperaturowe warunki brzegowe na jednej powierzchni domeny obliczeniowej. Praca zawiera jakościową analizę systemu

gruntowej pompy ciepła, której wyniki mogłyby zostać wykorzystane w procesie projektowania gruntowych sprężarkowych pomp ciepła.

Abstract

Present work concerns the CFD analysis of the Field type ground heat exchanger and its influence on the compressor heat pump performance. The coaxial vertical ground heat exchanger has been chosen as in most studies the U-pipe is being considered (Yang et al., 2010). Therefore, Field type ground heat exchanger's heat-flow characteristics are not available in the literature. Conjunction of 0D-3D level programming enabled FGHE-coupled compressor heat pump system analysis in terms of a quasi-steady continuous work lasting 170 hours. The ground coupled compressor heat pump may work in the monovalent system and complitely fulfil demand on heat, however, the heat exchange system of the low heat source needs to be designed in a proper way. Additionally, the CHP working medium needs to be chosen carefully (Bohdal et al., 2015). The CFD simulations were executed using a commercial software. Compressor heat pump cycle calculations were carried out using the author's computational programme. The FGHE of varying geometry was investigated in terms of a long term continuous work. Varying temperature boundary conditions were taken into account. This work provides qualitative data, which may be useful at ground coupled compressor heat pump system modelling.

Słowa kluczowe:
Gruntowy wymiennik ciepła typu Fielda, 0D-3D, sprężarkowa pompa ciepła

Key words:
Field type ground heat exchanger, 0D-3D, compressor heat pump