Numerical analysis of heat exchanger with uniform heat flux used in heat pumps systems

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Abstract. The paper presents a numerical analysis of an innovative heat exchanger with uniform heat flux, integrated as a cold source, for heating and air-conditioning systems which are equipped with heat pumps. The ground-water or water-water surface heat exchanger type is modelled, having variable geometry, uniform efficiency and heat flux along the system. The purpose of the work is to analyse a heat exchanger with uniform thermal flux, in order to offer an alternative to actual technical solutions using polyethylene pipes mounted in parallel on horizontal or vertical drilling. For typical geothermal heat exchangers, both the surface and the depth are characterized by non-uniform exploitation of the soil. The uniformity of the thermal load of the earth mass can be an energy efficiency solution in terms of optimizing the storage capacity and consequently the reduction of the land used, respectively the length of the drilling needed for mounting the source. The analysed heat exchanger with uniform thermal flux, designed to achieve low or medium sources of thermal energy, offers an efficient energy consumption, being environmentally friendly and has a reduced relative cost. It can be an attractive alternative for the residential buildings or Nearly Zero-Energy Buildings (NZBE).

1. Introduction

The heat pump domain has been of interest in Europe since the 1970s in Switzerland and the 1980s in Sweden, when an intense program of tracking behaviour over time and the life span of these systems has begun [1]. Shortly, it was found that the best quantification of heat pump quality is given by their coefficient of performance (COP), and the following studies, research and tests led to its progressive increase. Research from the University of Ontario, 2011, on the thermodynamic behaviour of hybrid geothermal heat pump systems, has led to the conclusion that they have superior performance over conventional systems [1, 2].

When the intrinsic efficiency of the system has reached a considerable level of performance, the studies from literature have focused on improving the conditions of the heat extraction / injection into the storage material [3]. Thus, in 2013, at the University of Technology in Nicosia, Cyprus, studies are started on the geothermal properties of the soil used for heat pump systems. Also, studies have been carried out at the Perpignan Via Domitia University in France on the improvement of geothermal drills with vertical boreholes, controlling the thermal conductivity of the bentonite used [4].

Available data on the European geothermal heat pump (GSHP) market reveals an interesting picture showing the existence of stable markets and the development of some new ones - as shown in Figure 1 and Figure 2 [5].

EU legislation on heat pump systems is not fully resolved yet, with large differences between countries, due to a number of specific factors such as: geological conditions, level of development, financial incentives offered by state institutions etc. [13-16]. This is the main reason why legislation cannot be fully harmonized [17-19].

Most studies from literature have focused on system analysis using geothermal heat pumps equipped with different types of heat exchangers with soil [8-10]. The main conclusion consists of that the most important element that ensures the operation of the heat pumps at optimal parameters is the geothermal
heat exchanger [6-10]. Most often, geothermal heat exchangers are characterized by the global heat transfer coefficient ($K$) (W/m²·K) [11, 12].

During the present study, a heat exchanger with uniform thermal flux is analysed, in order to offer an alternative to actual technical solutions using polyethylene pipes mounted in parallel on horizontal or vertical drilling.

2. Problem description

The purpose of this research is to realize the numerical analysis of an innovative heat exchanger in order to obtain conclusive data regarding the velocities (magnitude, spectra, vectors and path lines) and temperatures (spectra and values) recorded during operation. Using these results, the operating parameters and efficiency of the heat exchanger are evaluated. The heat exchanger subjected to analysis is part of the schematic diagram of the experimental stand presented in Figure 2.

![Functional scheme of the experimental stand](image)

**Figure 2.** Functional scheme of the experimental stand.

The main elements of the system are: 1 - heat exchanger, 2 - storage tank, 3 - rotameter, 4 - heat source - electric heater with circulation pump, 5 – hot water accumulator, 6 - manometer, 8 - distribution...
pipelines, 9 – backup circulation pump, 10 - valves, ST/1 ... 13 - temperature sensors, PdC - heat pump, VC - fan coil, data acquisition station.

The analysed heat exchanger has a special geometry, consisting of a distributor (D) and a collector (C), connected to each other by means of 20 copper pipes, Cu15x1 mm. Figure 3 shows an overview of the model analysed and some images of the real heat exchanger.

![Figure 3. Heat exchanger: a) heat exchanger-heat storage ensemble; b) images of the real model.](image)

The particularity of this exchanger consists in the circulation of the thermal agent, determined by the configuration of the distributor and the collector which are separated by alternating sectors. Thermal agent circulation is forced to take place in an imposed direction between the input and output sectors, respectively from top to bottom and from bottom to top, alternatively. Thus, the average temperature of the heat transfer is evenly distributed throughout the surface of the exchanger.

Consequently, the thermal flux dependent on the product of the two parameters \( Q_i = \varphi \cdot (S_i \cdot T_i) \), is constant.

The heat exchanger analysed is made of high thermal conductivity material (D/C and pipes made of copper), with a transfer capacity superior to the exchangers made of polyethylene pipes. It is designed to be used as a cold low and medium depth source, required for systems equipped with geothermal heat pumps with mechanical vapor compression. It works with hot water or glycol between the heat pump and the source used. The heat flux transmitted by small scale heat exchangers is calculated according to the following relationship (1).

\[
Q = G \cdot \rho \cdot c \cdot (T_{in} - T_{out}) \quad (1)
\]

The global heat transfer coefficient (\( K \)) is determined using the following mathematical expression:

\[
K = \frac{1}{\frac{1}{\pi \alpha_l D_i^2} + \frac{1}{2 \pi \lambda} \ln \frac{D_i}{D_e} + \frac{1}{\alpha^*}} \quad [W/m^2\cdot°C] \quad (2)
\]

where:
- \( \rho \) [kg/m\(^3\)] - density of thermal agent;
- \( c \) [kcal/kg °C] – specific heat of thermal agent;
- \( T_{in} - T_{out} = \Delta T \) [°C] – temperature difference at heat pump;
- \( \lambda \) [W/m °C] – thermal conductivity of the pipes;
- \( D_i, D_e \) – inner, outer diameter of the pipes;
- \( \alpha_l \) – convective heat transfer coefficient from thermal agent to the pipe wall;
- \( \alpha^* \) – convective heat transfer coefficient from pipe wall to the soil.
Figure 4. Details of heat exchanger: a) front view; b) side view; c) top view; d) bottom view.

Figure 4 (c, d) shows the offset between the distributor and collector sectors, causing alternative circulation of the agent through the fascicle of pipes.

The main constructive characteristics of the analysed heat exchanger are presented in Table 1.

| Table 1. Description of the model of the heat exchanger |
|--------------------------------------------------------|
| Dimensions [mm]                                        |
| - height ($H$)                                         |
| - width ($L$)                                          |
| - depth ($B$)                                          |
| Material                                               |
| Copper                                                 |
| Structure                                              |
| Distributor (D)                                        |
| Fascicle of pipes                                      |
| Collector (C)                                          |
| Structure of D/C                                       |
| 10 separate sectors for thermal agent circulation       |
| Fascicle of pipes                                      |
| Cu 15x0.7mm                                            |
| 20 pieces                                              |
| Length of pipes $L_T$ [mm]                             | 400 |
| Heat exchange surface [m²]                             | 0.918 |
| Volume of heat exchanger [litre]                       | 15.81 |
| Mass of empty heat exchanger [kg]                      | 6.17 |
| Length of thermal agent path inside the exchanger [m]  | 8.24 |

3. Numerical approach
The geometry of the model, Figure 5, was realized using AutoCAD 3D and imported into ANSYS-Fluent software. The mesh was realized in ANSYS Meshing with different refinement for distributor,
collector and fascicle of pipes, with a particular interest given to the compartmentation of the D/C. Therefore, a total of 511874 cells were used for meshing. The flow inside the heat exchanger was considered turbulent, taking into account the velocities imposed, dimensions of the pipes and the resulting Reynolds number, with a turbulent intensity of 5%. The numerical simulation was realized using $k-\varepsilon$ Re-Normalization Group (RNG) model of turbulence, with enhanced wall treatment, which is more accurate and reliable for a wider class of flows than the standard $k-\varepsilon$ model [22]. During simulations, the inlet mass flow rate (0.2 m$^3$/h) and temperature (50 °C) were imposed, while the initial temperature of the storage medium (water) was 15 °C. Also, a 8 W/m$^2$K exterior convective heat transfer coefficient was used.

![Figure 5](image)

**Figure 5.** Geometry (a) and mesh (b) of the studied model.

The calculation is iterative, with hybrid initialization and convergence criteria of $10^{-6}$ for the energy equation and $10^{-3}$ for the pressure, velocities and continuity equations.

4. Results

Results of simulations consist of the heat exchanger inside temperature variation and on its outer surface and velocity magnitude and spectra for the front, lateral and back sections. Figures 6-14 exported from the ANSYS-Fluent software show the results of numerical modelling on the proposed reduced scale heat exchanger. Qualitative and quantitative aspects regarding the flow inside the heat exchanger and the distribution of operating temperatures can be observed. There are also obtained the quantitative data of the thermodynamic process which will be used in further calculations, Table 2.

4.1. Temperatures

The temperatures spectra, Figures 6-9, revealed a quasi-uniform distribution of values both inside the heat exchanger and on its surface. Taking into account the uniformity of the storage medium, it can be assumed that the heat flux transferred from the heat exchanger is also uniform on its entire surface. It can be observed that the temperature of the thermal agent in the front section has an average value of 50 °C, while the same value for the back section reaches values of 48 °C. Thus, despite the heat transfer along the thermal agent path inside the heat exchanger, the operating temperature near the outlet section is comparable to the inlet one, determining a smooth loading of the storage medium.
Figure 6. Distribution of temperatures on the surface of heat exchanger.

Figure 7. Contours of temperature – inside overview.

Figure 8. Contours of temperature: a) front section; b) lateral section; c) back section.
4.2. Velocities

In terms of velocities, Figures 10-14 emphasize the efficiency of the heat transfer because of the amplified turbulence phenomena determined by the compartmentation of the distributor and collector, where there is usually a high tendency of stagnation for the thermal agent.

**Figure 10.** Contours of velocity – inside overview.

**Figure 11.** Contours of velocity: a) front section; b) lateral section; c) back section.
Numerical modelling provides a good view of the qualitative aspects of flow and distribution of heat agent temperatures through the proposed heat exchangers. Also, a good correlation can be observed between literature values and those obtained by numerical modelling.
The performance of the heat exchanger is analysed from the point of view of the heat transfer efficiency as global heat transfer coefficient. During the operation of the system, a uniformity of the temperatures on the surface of the heat exchanger is noted. The results of the numerical modelling were extrapolated for an example close to the daily practice ($T_{ag\_term} = 32$ °C, $T_{st\_init} = 18$ °C) and the values of the heat exchanger parameters are determined. Table 2 shows the values of the thermal flux ($Q$) and the global heat transfer coefficient ($K$) for the heat exchanger analysed for different operating time intervals ($\tau$).

Table 2. Calculation of global heat transfer coefficient

| $q$ [m$^3$/h] | $\tau$ [h] | $T_{ag\_term}$ [°C] | $T_{st\_init}$ [°C] | $T_{st\_fin}$ [°C] | $Q$ [W] | $K$ [W/m$^2$.K] |
|---------------|-------------|----------------------|---------------------|-------------------|--------|------------------|
| 0.200         | 2           | 32                   | 18                  | 22.6              | 883.1  | 88.0             |
|               | 3           |                      |                     | 23.7              | 726.9  | 76.9             |

The proposed heat exchanger is a viable solution for use in systems equipped with heat pump and geothermal sources. The resulting global heat transfer coefficient has values between 76.9 ... 88.0 W/m$^2$.K. It is noted that this coefficient varies during the heat injection into the storage medium, decreasing once the temperature of the storage medium begins to increase.

According to the results, it has been found that by using the proposed heat exchanger a quasi-uniform loading of the storage medium is achieved, which is an important advantage in pre-dimensioning and correct evaluation of a system to be installed.

5. Conclusions
The main result of the study is that the heat exchanger achieves a constant heat flux ensuring uniform heating of the earth mass.

The proposed heat exchanger model is very well suited to new buildings with low availability for low-depth groundwater capture, equipped with ground-water or water-water heat pumps. Also, the proposed solution can successfully replace ground energy capture systems with deep drillings (100 to 200 m) at a reduced price and superior efficiency.

With regard to existing buildings equipped with cold-water heat pumps in the classical variant, the advantage of integrating the proposed model lies in the flexibility, the reduced amount of necessary works and the limitation of the intervention area.

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Acknowledgement: This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI - UEFISCDI, project number PN-III-P2-2.1-CI-2018-1491, within PNCDI III.