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Thermoelectric Heat Exchangers with Uniform Heat Flux Used In Heat Pump Systems: A Numerical Analysis

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Abstract

The novel heat exchanger with homogeneous heat flow, incorporated as a cold source for heating and air conditioning systems with heat pumps, is numerically analyzed in this work. The surface heat exchanger type for groundwater or water is modeled; it has variable geometry, uniform efficiency, and heat flux throughout the system. The work's goal is to analyze a heat exchanger with uniform thermal flux in order to provide a substitute for practical technical solutions that rely on parallel polyethylene pipes drilled horizontally or vertically. Non-uniform exploitation of the soil occurs at both the surface and the depth for conventional geothermal heat exchangers. The homogeneity of the earth mass's thermal load can be an energy-efficient way to maximize storage capacity and, as a result, reduce the amount of land required, or the distance that needs to be drilled in order to mount the source. The uniform thermal flux heat exchanger under analysis is a cost-effective and environmentally friendly solution for achieving low to medium thermal energy sources. Its uniform thermal flux also contributes to its efficient energy usage. For residential buildings or nearly zero-energy buildings (NZBE), it might be a desirable substitute.

Keywords: Heat Exchanger, Heat Pump, Energy

1. Introduction

Since the 1970s in Switzerland and the 1980s in Sweden, when a comprehensive program of tracking behavior over time and the lifespan of these systems began, the heat pump domain has attracted attention in Europe. It was quickly discovered that the best way to quantify the quality of a heat pump is to look at its coefficient of performance (COP), and the subsequent tests, studies, and research all contributed to its gradual rise. According to 2011 research from the University of Ontario, hybrid geothermal heat pump systems perform better than traditional systems due to their thermodynamic behavior.

The improvement of the heat extraction/injection conditions into the storage medium has been the subject of literature studies once the system's intrinsic efficiency has reached a significant level of performance. Thus, research on the geothermal characteristics of the soil utilized for heat pump systems began in 2013 at the University of Technology in Nicosia, Cyprus. Furthermore, research has been done at the French university Via Domitia in Perpignan on how to make geothermal drills better by adjusting the heat conductivity of the bentonite used in the drills' vertical boreholes.

As seen in Figures 1 and 2, the data that is currently available on the European geothermal heat pump (GSHP) industry paints an intriguing picture of the existence of stable markets as well as the emergence of certain new ones.

There are still many disparities in EU law regarding heat pump systems between member states because of a variety of unique circumstances, including geological conditions, degree of development, financial incentives provided by governmental bodies, etc. The primary reason why complete harmonization of legislation is impossible is this.

The majority of research studies found in literature have concentrated on system analysis with geothermal heat pumps that are outfitted with various kinds of soil heat exchangers. The primary conclusion is that the geothermal heat exchanger is the most crucial component in ensuring that the heat pumps operate at their best. A common metric used to describe geothermal heat exchangers is the global heat transfer coefficient (K) (W/m2.K).

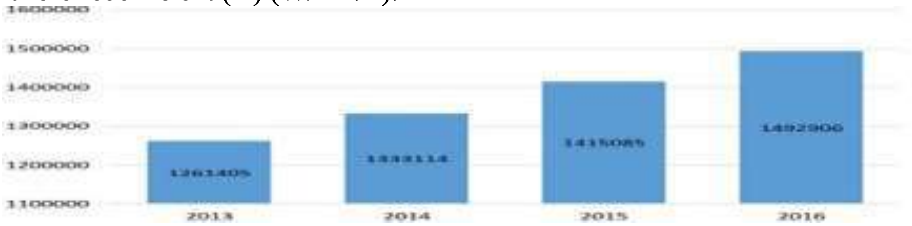


Figure 1. a) Energy produced (TWh) with heat pumps in Europe in 2014; b) Number of geothermal heat pump units in operation in Europe 2013-2016.

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

In order to gather definitive information on the temperatures (spectra and values) and velocities (magnitude, spectra, vectors, and path lines) recorded during operation, this research aims to perform a numerical analysis of a novel heat exchanger. These findings are used to assess the heat exchanger's efficiency and operating parameters. Figure 2 shows the schematic diagram of the experimental stand, which includes the heat exchanger that is being analyzed.

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.
This exchanger's unique feature is the way the thermal agent circulates, which is governed by how the distributor and collector are arranged to be separated by alternating sectors. The forced direction of thermal agent circulation is from top to bottom for the input sector and, alternately, from bottom to top for the output sector. As a result, the exchanger's surface has an even distribution of the average temperature caused by heat transmission.
Consequently, the thermal flux dependent on the product of the two parameters $Qi = \varphi \cdot (Si \cdot Ti)$, 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).

$$Q = G \cdot \rho \cdot c\,(Ti - Tout) \qquad (1)$$

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

$$K = \frac{1}{\frac{1}{\pi \alpha_i D_i} + \frac{1}{2\pi\lambda} \ln\frac{D_i}{De} + \frac{1}{\alpha^*}} \ [\mathrm{W/m^2 \cdot {}^\circ C}] \qquad (2)$$

where: ρ [kg/m^3] - density of thermal agent; c [k_{cal} /kg·˚C] – specific heat of thermal agent;
$Ti - Tout = \Delta T$ [˚C] – temperature difference at heat pump; λ [W/m·˚C] − thermal conductivity of the pipes; D , De − inner, outer diameter of the pipes; αii − convective heat transfer coefficient from thermal agent to the pipe wall; α^* − convective heat transfer coefficient from pipe wall to the soil.

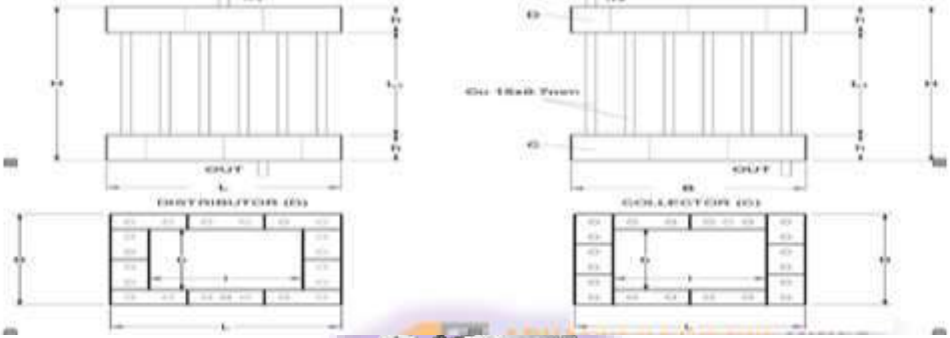


Figure 4. Details of heat exchanger: a) front view; b) side view; c) top view; d) bottom view.

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)	H = 600 L = 360 B = 360
Material Distributor (D) Structure	Fascicle of pipes Collector (C)
Structure of D/C thermal agent circulation	10 separate sectors for
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

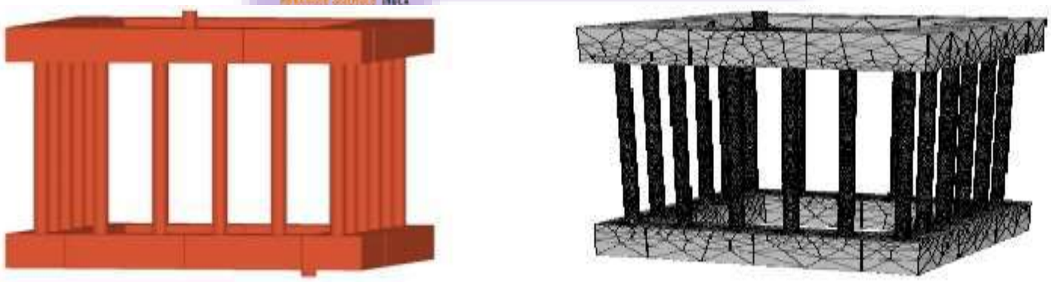
3. Numerical approach

AutoCAD 3D was used to create the geometry of Figure 5, which was then loaded into the ANSYS-Fluent program. With distinct refinements for the distributor, collector, and fascicle of pipes, the mesh was implemented in ANSYS Meshing, with a focus on the D/C compartmentation. As a result, 511874 cells in total were 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-ε 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-ε model.

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 $W/m^2 \cdot K$ exterior convective heat transfer coefficient was used.

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

The heat exchanger's internal temperature variation, its external surface temperature variation, and the velocity magnitude and spectrum for the front, lateral, and rear sections are all included in the simulation results.

The results of numerical modeling on the suggested reduced size heat exchanger are displayed in Figures 6–14, which were exported from the ANSYS-Fluent program. It is possible to observe both qualitative and quantitative characteristics of the heat exchanger's flow as well as the distribution of its operating temperatures. Additionally, Table 2 contains the quantitative thermodynamic process data that will be used in future computations.

4.1. Temperatures

The heat exchanger's surface and interior both showed a quasi-uniform range of values, as seen by the temperature spectra in Figures 6–9. It is reasonable to assume that the heat flux delivered from the heat exchanger is homogeneous along its whole surface given the uniformity of the storage medium.

It is evident that the average temperature of the thermal agent in the front portion is 50 °C, but the same temperature in the back area is 48 °C. As a result, the operating temperature close to the outlet portion is equivalent to the intake section, ensuring a smooth loading of the storage medium even with heat transfer along the thermal agent path inside the heat exchanger.

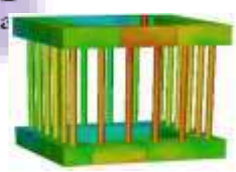


Figure 6. Distribution of temperatures on the surface of heat exchanger.

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.

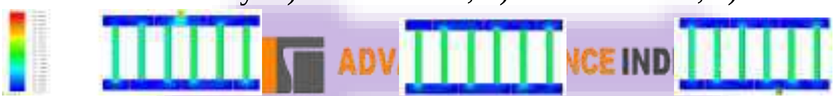


Figure 12. Velocity vectors: a) front section; b) lateral section; c) back section.

Figure 13. Velocity vectors: a) distributor section; b) collector section.

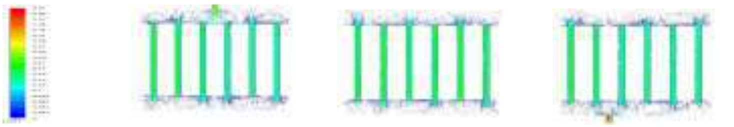


Figure 14. Velocity path lines: a) front section; b) lateral section; c) back section.

The qualitative features of the flow and distribution of heat agent temperatures through the suggested heat exchangers are well-represented by numerical modeling. Additionally, there is a strong correlation between the values from the literature and the numerical modeling results.

The heat transfer efficiency, also known as the global heat transfer coefficient, is used to analyze the heat exchanger's performance. The surface of the heat exchanger exhibits a consistent temperature during system operation.

The heat exchanger parameters are found by extrapolating the numerical modeling findings for a scenario that is similar to everyday life (Tag_term = 32 °C, Tst_init = 18 °C). The heat exchanger's thermal flux (Q) and global heat transfer coefficient (K) values for various running time intervals (τ) are presented in Table 2.

Table 2. Calculation of global heat transfer coefficient

q	τ	Tag_term	Tst_init	Tst_fin	Q	K
[m^3/h]	[h]	[°C]	[°C]	[°C]	[W]	[$W/m^2 \cdot K$]
	1			21.2	883,1	88,0
0.200	2	32	18	22.6	744,3	78,2
	3			23.7	726,9	76,9

The suggested heat exchanger is a workable option for systems that have geothermal and heat pump energy sources. The global heat transfer coefficient that is obtained ranges from 76.9 to 88.0 W/m2.K. It is observed that this coefficient fluctuates when heat is injected into the storage medium and then starts to decrease as the temperature of the medium rises.

The findings show that a quasi-uniform loading of the storage medium may be obtained by employing the suggested heat exchanger, which is a significant benefit for accurately evaluating and pre-dimensioning a system that will be implemented.

Conclusions

The study's primary finding is that a continuous heat transfer is achieved via the heat exchanger, guaranteeing even heating of the earth's mass.

The suggested heat exchanger type works exceptionally well with newly constructed buildings that have water- or ground-water heat pumps but limited availability for low-depth groundwater capture. Additionally, at a lower cost and with higher efficiency, the suggested approach can successfully replace ground energy capture systems with deep drillings (100–200 m).

The advantages of incorporating the suggested model with relation to current buildings outfitted with cold-water heat pumps in the classical variation are its flexibility, the decreased amount of labor required, and its restriction on the intervention area.

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