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EXPERIMENTAL ANALYSIS OF INNOVATIVE HEAT EXCHANGER WITH UNIFORM HEAT FLUX USED IN HEAT PUMPS SYSTEMS

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Abstract

The study presents the experimental testing of a heat exchanger with uniform thermal flux (HEUTF), used as a cold source in HVAC systems with heat pumps. A water-water heat exchanger is tested, having a special geometry, with uniform thermal flux along the system. The heat exchanger proposed consists of a distributor and a collector, connected to each other by means of 20 staggered copper pipes, being suitable for serving low or medium geothermal sources. The innovation consists in the uniformity of the heat flux along the entire length of the heat exchanger, due to the alternating circulation of the heat transfer fluid between collector and distributor. The work is focussed on offering a replacement to current technical solutions that are characterized by horizontal or vertical polyethylene pipes connected in parallel. Unlike the typical geothermal heat exchangers, when the surface and the depth of digging determines a non-uniform loading of the soil, the present solution induces an improved level of uniformity regarding the thermal load of the storage medium, while the global heat transfer coefficient resulting from the experimental tests has values between 76.9 ... 110.7 $W/m^2 \cdot K$. The proposed solution is highly efficient in terms of maximizing the storage capacity and of decreasing the necessary surface for mounting the source.

Key words: beam of pipes, compact heat exchanger, geothermal sources, heat pump, heat flux

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1. Introduction

The field of heat pumping systems has become of interest in European countries since the 1970s, in Switzerland, and the 1980s, in Sweden. During this period, an intense program of analysing the behaviour during the lifetime of these systems has begun (Cazacu, 2016). It was concluded that the most appropriate quantification of heat pump efficiency is given by their coefficient of performance (COP), and with the help of the further studies, research and experimental tests it was progressively increased (Sebarchevici, 2013). Researches on the thermodynamic behaviour of hybrid geothermal heat pump systems (Cazacu, 2016; Prică, 2015) has led to the statement that they have superior performance over conventional ones.

The moment when the internal efficiency of the system reached an adequate level of performance coincided with an increase in the number of studies in literature that are focussing on improving the performance of the heat extraction/injection into the storage medium. Studies from University of Technology in Nicosia, Cyprus, 2013 aimed on the geothermal properties of the soil used for heat pump systems, while at the Perpignan Via Domitia University in France, the improvement of geothermal drills with vertical boreholes is analysed by controlling the thermal conductivity of the bentonite used (Cazacu, 2016).

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The European Geothermal Heat Pump market reveals the tendency of the countries with stable markets and the development of some new ones (Fig. 1) (Gavriliuc, 2015). The European legislation regarding the field of heat pump systems is not fully resolved yet, having important differences between countries (Popovici and Hudișteanu, 2019). The main reasons why legislation cannot be fully harmonized are the existence of various geological conditions, country development index or financial support programs offered by governments (AG 31-008, 2002; Bonin, 2015; Ekman et al., 2008; EurObserv'ER, 2016; Forsén et al., 2008; NRC, 2004; Rehman, 2011).

The studies from literature are regarding on the systems using geothermal heat pumps equipped with different types of water-water or water-ground heat exchangers (ASHRAE, 1995, 2012, 2013). According to these, one of the most important elements that ensures an optimum operation of the heat pump systems is the geothermal heat exchanger (Gabor et al., 2016; Gavriliuc, 1999, 2016; Neacsu et al., 2010) and the heat storage medium (Klimašauskas, 2020). The main parameter that characterizes geothermal heat exchangers is the global heat transfer coefficient *K* [$W/m^2 \cdot K$] (Sebarchevici, 2013; Gabor et al., 2017), which represents also the main research target of the present study.

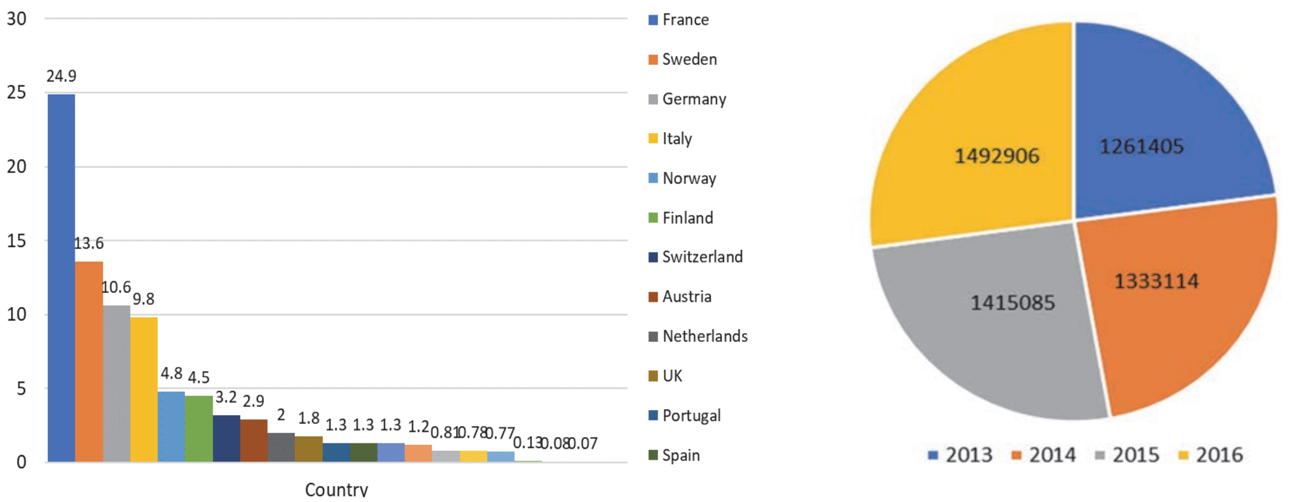
This experimental research presents the analysis of the operating parameters of an innovative heat exchanger with uniform heat flux (HEUTF) that offers a replacement to current technical solutions that are characterized by horizontal or vertical polyethylene pipes connected in parallel (Raymond et al., 2015). The novelty of the research consists in conception of a heat exchanger with a special geometry and achieve, by experimental tests, conclusive data regarding the velocities, flow rates, temperatures and global heat transfer coefficient.

2. Experimental setup

The experimental results are used for determining the heat flux and heat transfer coefficient of the heat exchanger evaluated. The images of the heat exchanger subjected to analysis are presented in the following images in Fig. 2. The main elements of the proposed heat exchanger are presented in Figs. 3-4. The model was validated by preliminary numerical analysis conducted for this special arrangement of the main components, that is used in order to obtain an evenly distributed average temperature of heat exchange over the entire surface of the exchanger (Popovici and Hudișteanu, 2019).

The heat exchanger with uniform thermal flow (HEUTF) integrated as a cold source for heating and air-conditioning systems equipped with heat pumps is a small-scale geothermal heat exchanger with a high thermal conductivity beam of pipes. 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, Cu15x0.7 mm. Fig. 5 shows an overview of the model analysed and the position of the heat exchanger inside the storage medium. The particularity of this exchanger consists in the circulation of the heat transfer fluid, determined by the configuration of the distributor and the collector which are separated by alternating sectors.

The heat transfer fluid circulation is forced to take place in a strict direction between the inlet and outlet sectors, respectively from top to bottom and from bottom to top, alternatively (Fig. 6). Thus, the average temperature of the heat transfer is evenly distributed throughout the surface of the exchanger.

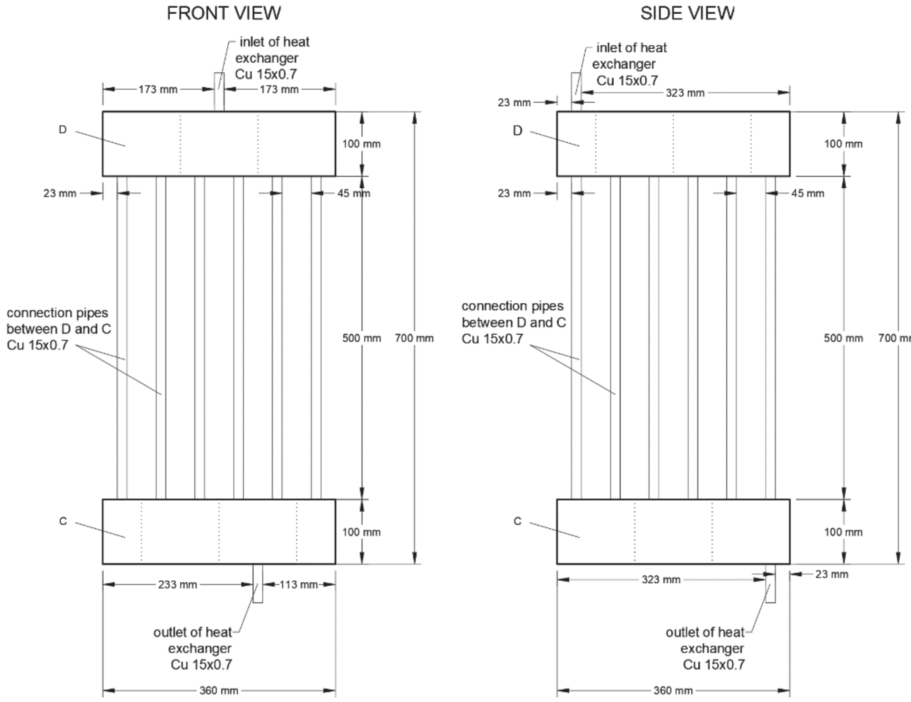


(a) (b)

Fig. 1. (a) Energy produced (TWh) by heat pumps in EU in 2014 (EHPA, 2020),
(b) Number of geothermal heat pump units in operation in EU 2013-2016 (Statista, 2020)

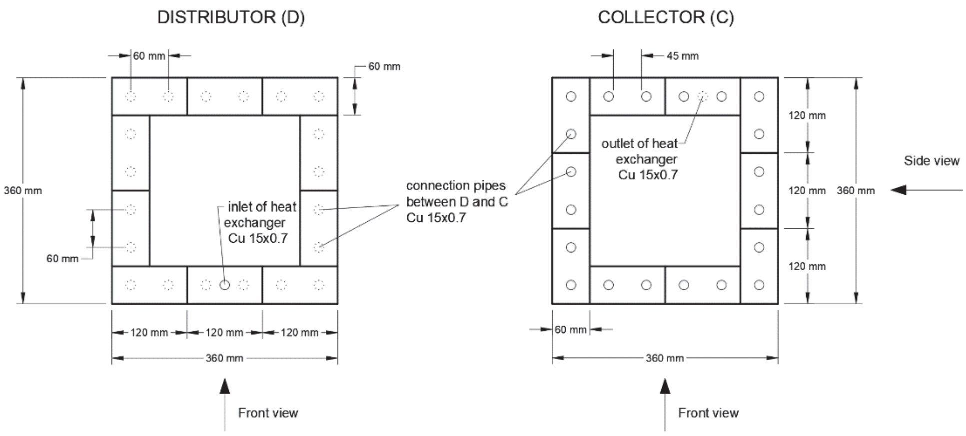
(a) (b)

Fig. 2. Images of the heat exchanger: (a) front view, (b) side view



(a) (b)

Fig. 3. Details of the heat exchanger: (a) front view, (b) side view



(a) (b)

Fig. 4. Details of the heat exchanger: (a) - distributor, (b) collector

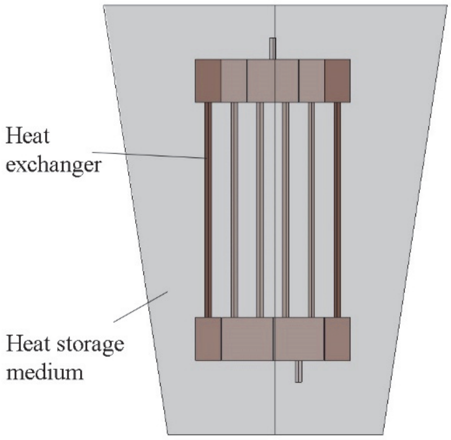
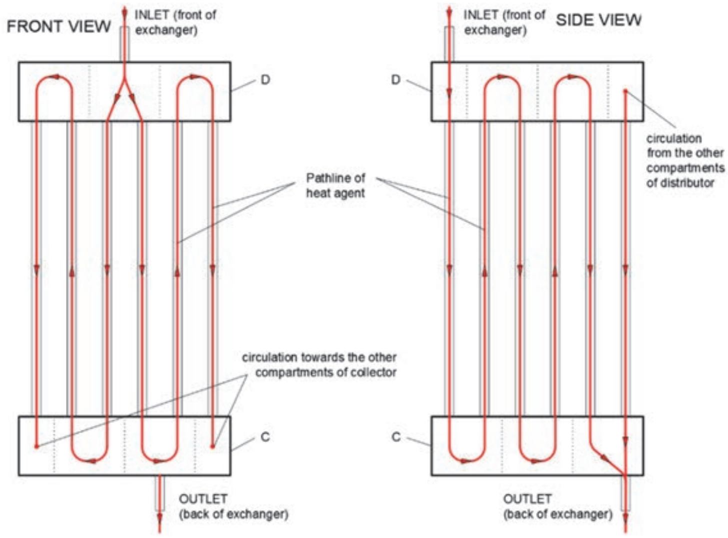


Fig. 5. Position of the heat exchanger inside the storage medium



(a) (b)

Fig. 6. The heat transfer fluid circulation through heat exchanger: (a) front view, (b) side view

The heat exchanger analysed is made of high thermal conductivity material (distributor/collector 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/hot source for low and medium depth, required for systems equipped with geothermal heat pumps with mechanical vapor compression. It works with water as heat transfer fluid between the heat pump and the storage medium used. The heat flux (Q) transmitted by the small-scale heat exchanger is calculated according to the following relationship (Eq. 1):

$$Q = G \cdot \rho \cdot C \cdot (T_{in} - T_{out}) \ [W] \qquad (1)$$

where: ρ [kg/m^3] - density of heat transfer fluid; c [J/kg·K] – specific heat of heat transfer fluid; $T_{in} - T_{out} = \Delta T$ [K] – temperature difference at heat pump; G [m^3/s] – volumetric flow rate.

The global heat transfer coefficient (K) is determined using the following mathematical expression (Eq. 2):

$$K = 1/[1/(\pi \cdot \alpha_i \cdot D_i) + (1/2 \cdot \pi \cdot \lambda)) \cdot \ln(D_i / D_e) + 1/\alpha^* \ [W/m^2K] \qquad (2)$$

where: λ [W/m·K] – thermal conductivity of the pipes; D_i, D_e [m] - inner, outer diameter of the pipes; α_i [W/m^2·K] - convective heat transfer coefficient from heat transfer fluid to the pipe wall; α^* [W/m^2·K] - convective heat transfer coefficient from pipe wall to the storage medium.

During this study, the HEUTF is used to inject thermal energy into the storage medium (water), but it can be used also to extract thermal energy from soil/water or to recover heat from technological processes. It works with an intermediate heat transfer agent (water), between the heat pump exchanger and the storage medium used. HEUTF represents a heat exchanger with modular construction, designed with variable geometry, with uniform heat transfer and extraction throughout the system.

The uniformity of the thermal flux, which is the main characteristic of the proposed solution, ensures a balanced loading of the earth mass including the drilling length reduction necessary for the storage medium. The uniformity can be also achieved by series connection of the multiple HEUTF with increasing lengths along the heat transfer fluid circulation. The proposed small-scale heat exchanger is tested in three constructive variants (Table 1), obtained by varying the length of the pipes:

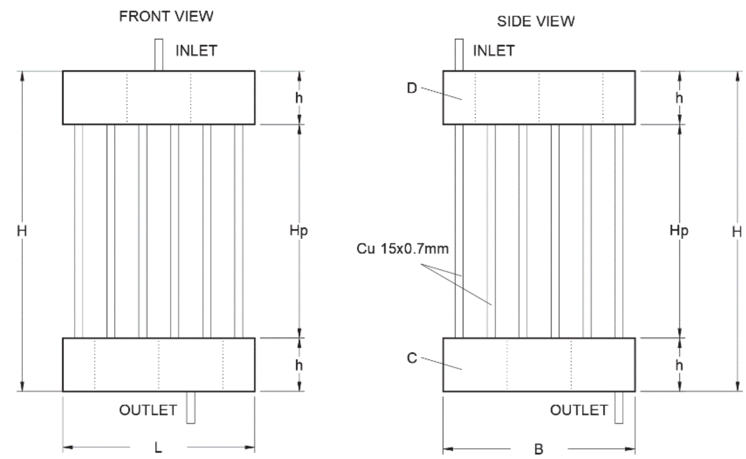
- HEUTF 60: H = 600 mm, H_p = 400 mm;
- HEUTF 70: H = 700 mm, H_p = 500 mm;
- HEUTF 80: H = 800 mm, H_p = 600 mm.

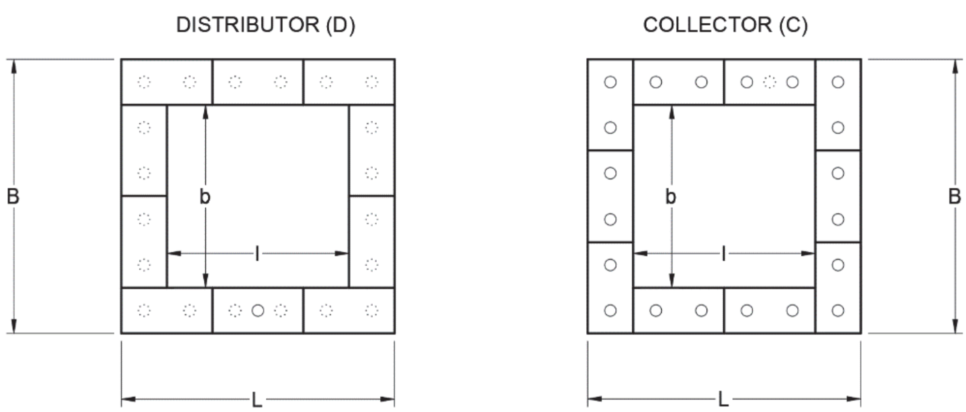
The structure of distributor/collector, both composed of 10 separate sectors for the circulation of the heat transfer fluid is presented in the following image (Fig. 7).

The main purpose of the analysis of the efficiency of the heat exchangers is to determine the global heat transfer coefficient by measuring the inlet and outlet temperatures of the heat transfer fluid, as well as the operating conditions of the heat pump.

The output temperature of the heat transfer fluid from the heat exchanger is the determining factor in the process of extracting/injecting heat from/to the storage medium, quantifying the energy efficiency throughout the system. The technical details of the heat exchange parameters of the 3 models of heat exchangers proposed are recorded in Table 2. In order to verify the energy performance of the proposed solution, an experimental research program was carried out on the small-scale physical model.

Table 1. Dimensions and structure of the heat exchangers analysed

Model	***HEUTF60***	***HEUTF70***	***HEUTF80***
Dimensions			
Dimensions [mm]: – height (H) – width (L) – depth (B)	H = 600 L = 360 B = 360	H = 700 L = 360 B = 360	H = 800 L = 360 B = 360
Material	Copper		
Structure	Distributor (D) Beam of pipes (20 pieces) Collector (C)		



(a) (b)

Fig. 7. Sectors of circulation of heat agent inside (a) distributor (D), (b) collector (C) dimensions of D and C:
- outer contour L x B x h [mm]: 360 x 360 x 100; - inner contour l x b x h [mm]: 240 x 240 x 100

Table 2. Technical details of the analysed heat exchangers

Model	***HEUTF60***	***HEUTF70***	***HEUTF80***
Beam of pipes	Cu 15x0.7mm		
	20 pieces		
Pipe length H_p [mm]	400	500	600
Heat exchange surface [m^2]	0.918	1.012	1.106
Volume of the heat exchanger [L]	15.81	16.17	16.52
Mass of empty heat exchanger [kg]	6.17	6.80	7.43
Montage	Vertical		
Inlet/Outlet connection	External cylindrical thread DN15, according to DIN ISO 228/1		
Length of heat transfer fluid path inside the exchanger [m]	8.24	10.25	12.26

The main objectives of the study were:

- determining the functional characteristics of the proposed heat exchangers;
- determining the global heat transfer coefficient of the exchangers;
- establishing the energy efficiency of the exchangers.

The experimental program was performed taking into account the variation of the operating parameters of the heat transfer fluid (temperatures, flow rates), as well as the temperature of the storage medium. The maximum temperatures and flow rates used in the tests for the injection of heat into the storage medium (water) were in the following range:

- inlet temperature of heat transfer fluid: T_{in} = 30....50 ºC;
- heat transfer fluid flow rate: q = 200...500 l/h.

The experimental program was carried out through the separate testing of the 3 proposed heat exchangers, using the experimental set up shown in Fig. 8, whose functional scheme is represented in Fig. 9. The tests were aimed at measuring the operating parameters of the proposed small-scale exchangers and their efficiency. The main components of the system are (Figs. 8-9): 1 - heat exchangers (inside storage tanks), 2 - storage tanks, 3 - rotameter, 4 - heat source - electric heater with circulation pump, 5 – hot water accumulator, 6 - manometer, 7 – safety valve, 8 - distribution pipelines, 9 – backup circulation pump, 10 - valves, ST/1 ... 13 - temperature sensors, D/C – distributor/collector of the system, HP - heat pump, FC - fan coil, DAS - data acquisition station.

The experiments were achieved according to the parameters presented in Table 3. The experimental program included a series of several tests, by varying the parameters of the heat transfer fluid and the regime of heat injection using the proposed small-scale heat exchangers. The characteristics of the main instruments used for measuring temperatures and flow rates are presented in Table 4. All the temperature sensors used together with MS5 Data Logger were supposed to a calibration bath at constant temperature to let the two devices adjust for 30 minutes to the temperature point.

Table 3. The values for the main parameters involved during experiment

Parameter	***Value***
Heat transfer fluid and storage medium	Water
Nominal heat flow rate [kg/s]	0.056
Density of heat transfer fluid [kg/m^3]	995.56
Dynamic viscosity of the heat transfer fluid [Pa·s]	1.0×10^{-3}
Specific heat of heat transfer fluid [J/kg·K]	4110
Initial temperature of heat transfer fluid [°C]	55
Initial temperature of the storage medium [°C]	15
Operating pressure of heat transfer fluid [bar]	0.5...6

Fig. 8. The experimental stand - storage tanks and secondary circuit

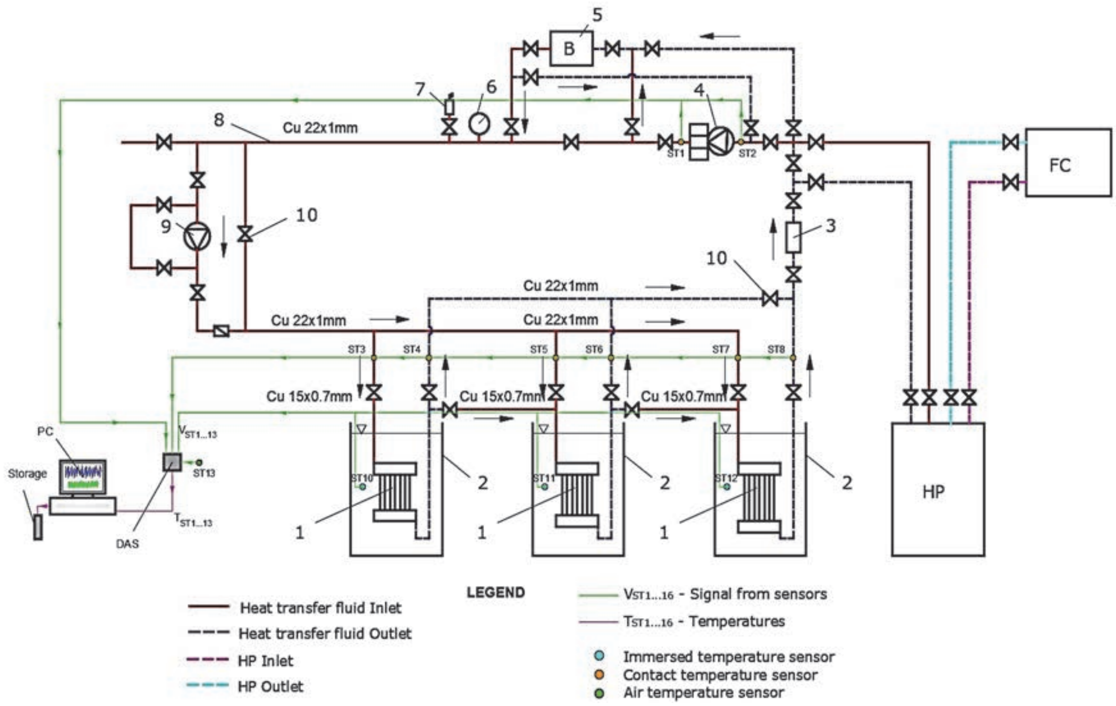


Fig. 9. Functional scheme of the experimental stand

Table 4. The accuracy and range of measuring devices

No.	*Equipment*	*Use*	*Characteristics*
1	Data acquisition system (DataLogger MS5) http://www.comet-datalogger.hu/ english/monitoring-system-ms5.htm	Read signal from temperature sensors	16 channels
2	Immersed temperature sensor (Pt1000TG68/0 universal probe) - www.tequipment.net/Comet/SN233/ Temperature-Probes/	Measure temperature of storage medium (suspended in water storage tank)	Range from -30 to +150°C Accuracy class of element * ± (0,15 + 0,002 ∣t∣) in °C
3	Contact temperature sensor (PTS350-5/0 surface probe) - www.tequipment.net/Comet/SN182/ Temperature-Probes/#description	Measure temperature of heat transfer fluid (attached to pipes)	Range from -30 to +130°C Accuracy class of element * ± (0,15 + 0,002 ∣t∣) in °C
4	Air temperature sensor (Pt1000TG7/0 surface probe) – www.tequipment.net/Comet/SN167/ Temperature-Probes/	Measure temperature of outside air (suspended in air)	Range from -30 to +200°C, Accuracy ±(0,15+0,002 ∣t∣)
5	Flowmeter (HFB-2-05) www.dwyer-inst.com/Product/ Flow/Flowmeters/In-Line/ SeriesHF?Query=HFB-2-05#specs	Measure volumetric flow of heat transfer fluid	Range from 1...19 l/m water Accuracy: 4% FS over the entire field; 2.5% centre third of the measuring range; repeatability: 1% of scale
6	Electric heater www.hydronicsupplies.com.au/wp-content/uploads/2015/04/Laing-Electric-Heaters.pdf	Temperature control of heat transfer fluid	Heating capacity: 2000 W pump A1-150, 230V, 25W constant temperature thermostat with a range of 20°C to 80°C

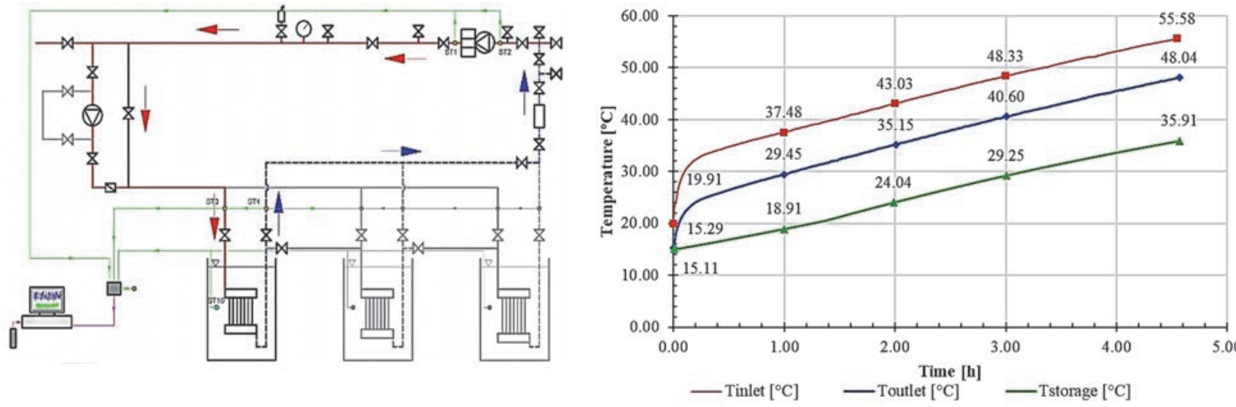
3. Results and discussion

A total of four experiments were conducted in this research. The results presented are based on a number of at least three preliminary repetitive tests for each experiment with approximately the same input parameters, that provided the same trend of the output data. Tests 1, 2 and 3 present the separate operation of each small-scale heat exchanger, and the results are presented in Figs. 10 -12. The duration of experiments varies between 3.5 and 5 hours.

The HEUTF60 and HEUTF70 testing (Figs. 10-. 11) presents similarities in terms of storage temperature variation, while the HEUTF80 (Fig. 12) determines a more accelerated heat transfer as well as an intensified tendency of increasing the temperature of storage medium.

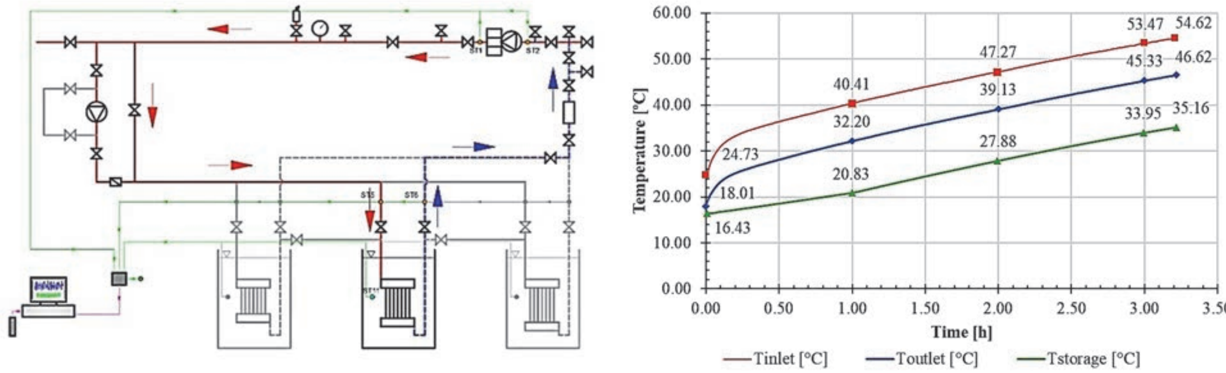
In Test 4, the experimental measurements were performed on the series connection of the proposed small-scale heat exchangers. Thus, in order to obtain the heat flux uniformity, the heat exchangers were successively connected from the smallest one (HEUTF60) at inlet, to the largest one (HEUTF80) at outlet. The results of the experiment are presented in Fig. 13. It was noticed that after some initial fluctuations in the first hours of operation, the temperatures in all the storage media begin to have approximately equal values (Fig. 13), meaning that the storage media started to be quasi-uniform loaded by the heat exchangers. This represents an important advantage in order to realize the correct dimensioning, forecasting and evaluation of a system to be installed.

The energy performances of the heat exchangers were analyzed from the point of view of the efficiency of the heat transfer, quantified as global heat transfer coefficient. The proposed heat exchangers were analyzed separately and the uniform loading of the storage medium (water) was also found when they are connected in series. Table 5 presents the values of the of the global heat transfer coefficient for each type of small-scale heat exchanger for various operation times (from 1 hour to 3 hours).



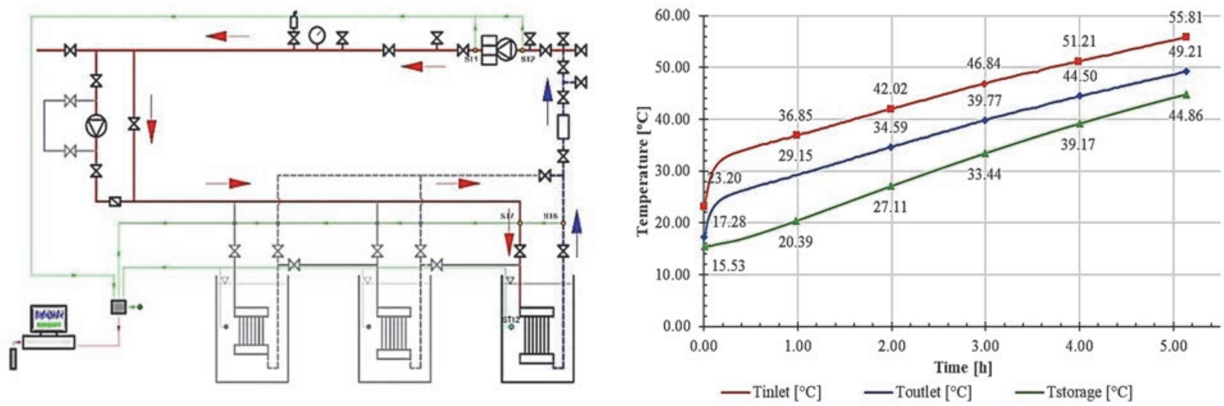
(a) (b)

Fig. 10. Test 1 - Operation of the first heat exchanger (HEUTF60, H = 600 mm, H_p = 400 mm): (a) functional scheme, (b) evolution of inlet, outlet and storage medium temperatures



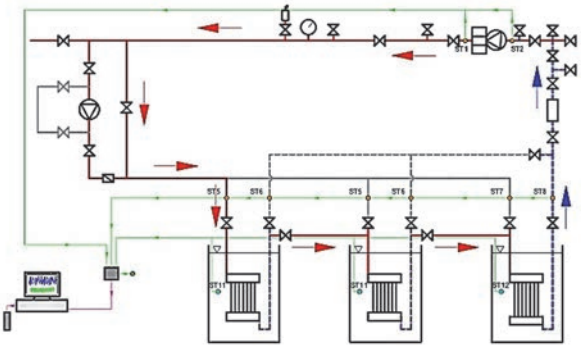
(a) (b)

Fig. 11. Test 2 - Operation of the second heat exchanger (HEUTF70, H = 700 mm, H_p = 500 mm): (a) functional scheme, (b) evolution of inlet, outlet and storage medium temperatures

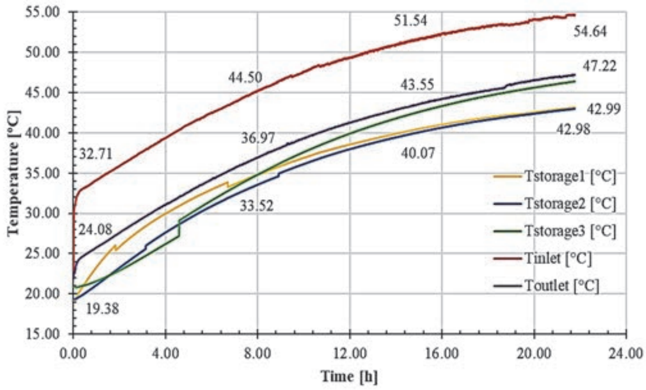


(a) (b)

Fig. 12. Test 3 - Operation of the third heat exchanger (HEUTF80, H = 800 mm, H_p = 600 mm): (a) functional scheme, (b) evolution of inlet, outlet and storage medium temperatures



(a)



(b)

Fig. 13. Test 4 - Analysis of the uniformity of the loading of the storage medium by series connection of the proposed exchangers (HEUTF60, 70, 80): (a) functional scheme, (b) evolution of inlet, outlet and storage medium temperatures

Table 5. The global heat transfer coefficient for each type of exchanger

Model	*HEUTF60*	*HEUTF70*	*HEUTF80*
Pressure loss [bar]	0.024	0.026	0.029
Operating time [h]	1 / 2 / 3	1 / 2 / 3	1 / 2 / 3
Average thermal flow during operation [W]	883.1 / 744.3 / 726.9	910.6 / 776.0 / 744.7	1176.3 / 970.8 / 823.7
Average global heat transfer coefficient during operation [W/m²·K]	88.0 / 78.2 / 76.9	93.8 / 84.5 / 82.0	110.7 / 105.9 / 103.1

It is found that the global heat transfer coefficient resulting from the experimental tests varies between 76.9...110.7 W/m²·K during the heat injection in the storage medium, decreasing once its temperature begins to rise. Taking into account the values of the global heat transfer coefficients from literature: 73.28…73.81 W/m²·K (Neuberger et al., 2014), 100 W/m²·K (Lamarche, 2019) at similar operating parameters, it is found that this type of exchanger has adequate results in order to represent a viable solution for use in heat pump systems and geothermal sources.

4. Conclusions

The main result of the study is that the proposed heat exchangers (HEUTF) achieve adequate global heat transfer coefficients (76.9 ... 110.7 W/m²·K) during operation and constant heat flux when they are connected in series, ensuring uniform loading of the storage medium.

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 characterized by deep drillings (100 to 200 m) at a reduced price and good efficiency.

HEUTF can be also used for existing buildings equipped with cold-water heat pumps in classical variant. The advantage of integrating the proposed model lies in the flexibility, the reduced amount of necessary works or space and the limitation of the intervention area.

There is expected an economic impact of implementing the solution developed on a large scale, at the level of a residential, public, commercial or industrial building for capitalizing the residual or renewable energy resources. Though, the reduction of costs can be achieved by using the proposed heat exchangers with high efficiency of extracting/injecting the thermal energy needed for heating, ventilation and air conditioning systems. The implementation of the analysed solution at the level of a building has a potential of reduced return on investment time, depending on the size and the destination of the consumer.

Given that the heat exchanger with uniform heat flux does not have moving elements and is made by using modern technologies of execution, it is possible to estimate an important operating life and an increased safety in operation.

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