ASSESSMENT OF THE INFLUENCE OF BOREHOLE HEAT EXCHANGER DESIGN ON A GROUND COUPLED HEAT PUMP SYSTEM

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Abstract - The paper presents the general concept of a ground coupled heat pump system that could be installed in a building belonging to University of Oradea. A short description of the consumer, together with base load and peak load energy consumption around the year, are also shown in the first part of the paper. Then, all design elements for the borehole heat exchanger (BHE) are presented and several scenarios are set. For each of them a simulation of mean fluid temperature is made for a time period of 20 years. Finally, results are analysed, and each case is discussed showing its advantages or disadvantages. At the end, conclusions are set.

Keywords: ground coupled heat pump, borehole heat exchanger, geothermal energy, fluid temperature simulation.

1. INTRODUCTION

Energy consumption per capita is considered to be an indicator of the living standards [1, 2, 3] and one may say that is a good thing to have a high energy consumption. But when it comes to the cost of energy, if taken into account not only the price of it, but the environmental implications of its production, it is better to have a lower energy consumption with a high efficiency of conversion.

Over the years, the European Commission was constantly concerned about the environment, global warming, and CO_2 footprint, issuing several regulations. It started with the Kyoto protocol (1997) where EC committed to an 8% reduction of a basket of six greenhouse gases during the first commitment period 2008-2012 (compared to 1990 levels) [4, 5]. But the most well-known catchword is ”20-20-20 by 2020” related to the second commitment period (2012-2020), although it is considered weaker than the previous one, having no binding obligations [6]. The European Union has deployed a leadership strategy in the international regime on climate change, based on the credibility of the development of its internal climate policy [7]. Finally, the post-2020 targets are divided in long term emission reduction for 2050 and a short-term having 2030 as target [8]. This most recent set of policy initiatives – the so-called European Green Deal - was approved in 2020 and has the overarching aim of making the European Union the world first “climate-neutral bloc” by 2050. It involves a series of regulations on clean energy, sustainable industry, building and renovation, farming, eliminating pollution, and sustainable mobility.

For the member states of the International Energy Agency, the energy use for space and water heating has remained stable since 2010, with heating energy intensities (i.e. final energy use per m^2) decreasing by only 2% per year since 2010 – just enough to offset no more than floor area growth [9]. Most reductions in heating energy intensity have resulted from stricter building energy codes that have improved the energy performance of new constructions and reduced space heating demand. After years of slow but steady decline, the share of coal, oil and natural gas boilers in global heating equipment sales fell under 50% in 2020 [9]. The market is slowly transitioning from a fossil fuel-dominated technology mix towards more efficient or lower-carbon solutions. Sales of heat pumps and renewable heating equipment such as solar hot water systems made up more than 20% of overall installations in 2020 [9].

If we are talking about Romania, its goals to reach the European Green Deal targets [10] are clearly expressed in the National Energy and Climate Plan [11]. The transition from fossil fuels towards renewable energies for covering the heat demand must be accelerated in order to increase energy independence. Heat pumps play an important role since they have a high efficiency and ground coupled heat pumps are even more efficient than air-to-air heat pumps [12].

2. GROUND COUPLED HEAT PUMP SYSTEM PROPOSED FOR UNIVERSITY OF ORADEA

The University of Oradea main campus is located in the south-western part of the city, on the shore of a very small river Peta, that is actually a geothermal spring coming to surface a few km away at Băile 1 Mai. Apart from the students’ dormitory buildings, the canteen and the sport halls, most of the buildings where the educational process takes place are historical ones. They were built at the end of the 19th century and accommodated for many years a school for law enforcement officers (Fig. 1).

All these old buildings must comply with the Historical Monuments Law as protected buildings and their refurbishment require special attention. From the energy point of view, external walls insulation, attic insulation, windows replacement are only a few actions that must be done, but solely without affecting stuccos and window frames that should be kept intact. As University of Oradea is focused on efficient use of energy and sustainable solutions for heating its buildings, it recently applied for a grant to fulfil its energy saving goals. The proposal was successful and refurbishment works should start in 2022.

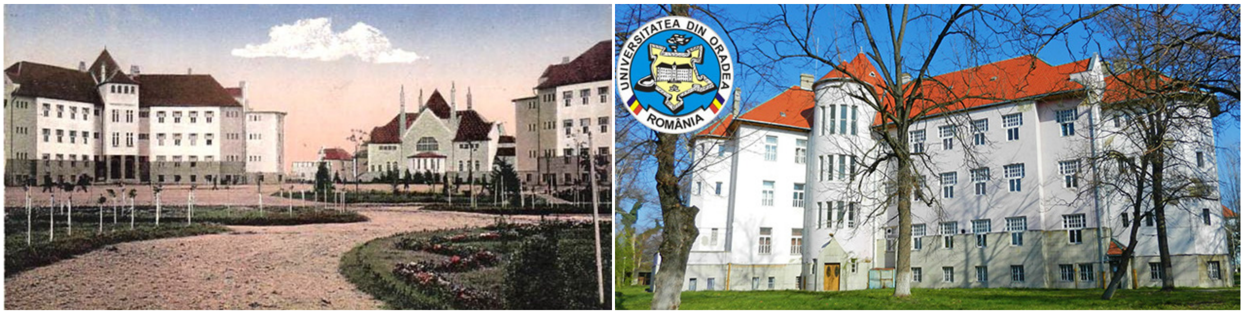

Fig. 1. A building of the University of Oradea main campus – then and now (100 years ago and present time)

This paper analyses the possibility of using a ground coupled heat pump (GCHP) system for heating one of the refurbished buildings. GCHP systems are complex heating and cooling systems that use the shallow ground as heat source or heat sink. They are also called geothermal heat pumps. They are included in a larger category of heat pump systems: the ground source heat pumps. This type of systems consists of three subsystems:

- the heat source sub-system;
- the heat transfer sub-system;
- the distribution and consumption sub-system.

The difference between ***ground source*** and ***ground coupled*** heat pumps is made by the heat source subsystem. The latter ones absorb heat from the ground using an intermediate fluid that circulates into a closed underground circuit. Therefore, ground coupled heat pump systems are also called closed loop heat pumps [13]. The goal of the intermediate fluid that circulates through the buried pipes is to exchange heat with the ground, they are often called *ground heat exchangers* [13].

For the chosen building, the peak load of the heating system was calculated to 38 kW and the annual energy consumption was considered 75.26 MWh. The monthly distribution of this energy was determined after daily energy consumption was calculated (Fig. 2) based on minimum, maximum and average daily temperature of the outside air.

The values of the monthly energy consumption are shown in Table 1.

Table 1. Monthly energy consumption (Q_{heat})

Month	Q_{heat} [MWh]	Month	Q_{heat} [MWh]
January	16.326	July	0
February	12.356	August	0
March	9.757	September	0.996
April	5.505	October	5.124
May	1.668	November	9.331
June	0.057	December	14.137

Beside the monthly consumption of thermal energy, another parameter that is important for the simulation is the peak heating load.

Fig. 2. Daily energy consumption of University of Oradea GCHP proposed system

This is set assuming a continuous operation of the heat pump for 12 hours, leading to a pronounced decrease of ground temperature. The peak load is also used to estimate the maximum possible temperature variation. The base load – monthly energy consumption – is important for calculating the ground temperature for long-term development (for instance, 20 years), while the peak load is used for checking if the maximum required load over a continuous operation period of 12 hours can be extracted under the general long-term development [14].

The above heating load is covered by a brine to water heat pump of 38 kW that has a coefficient of performance of 5.4. The heat pump represents the heat transfer sub-system of the proposed GCHP heating system.

The heat source sub-system depends on many parameters, including the available space for drilling the boreholes. Therefore, considering the green space that surrounds the analyzed building, a number of 10 borehole heat exchangers that have 130 m length are chosen. These two characteristics are common to all scenarios.

3. SIMULATION OF GROUND TEMPERATURE FOR GCHP SYSTEM FROM UNIVERSITY OF ORADEA CAMPUS

Since the ground temperature is strongly influenced by multiple factors, such as: type of BHE, diameter of borehole, depth of borehole, diameter and conductivity of the pipe from which the BHE is made of, shank space, type of fluid inside the BHE, flow rate of this fluid, distance between boreholes, configuration of boreholes, series factor, conductivity of grouting material, etc., all these parameters must be considered when the simulation is made.

Several scenarios were developed in order to establish the temperature variation of heat source fluid for different conditions and to determine the optimum scenario. Table 2 shows the numerical values of parameters, for each simulated scenario.

Table 2. Parameters of the simulated scenarios

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
Depth [m]	130	130	130	130	130	130	130	130	130
Borehole diameter [mm]	150	150	150	120,7	120,7	150	150	150	150
Type of BHE	double U	simple U	simple U	simple U	double U	simple U	simple U	simple U	simple U
Pipe diameter of BHE [mm]	32	40	40	25	32	40	40	40	40
Pipe wall thick-ness [mm]	3	3.7	3.7	2.7	3	3.7	3.7	3.7	3.7
Shank space [mm]	70	90	70	75	70	70	70	70	70
Pipe conducti-vity [W/m·K]	0.42	0.42	0.42	0,22	0.42	0.42	0.42	0.42	0.42
BHE configuration	2 x 5	3 x 4	6 x 3	2 x 5	4 x 7	5 x 6	5 x 6	6 x 3	2 x5
Borehole distance [m]	10	10	10	10	8	8	8	10	10
Series factor	5	2	10	1	2	2	1	1	1
Conductivity of grouting mate-rial [W/m·K]	0.8	1.5	2	0.8	2	2	2	2	2
Type of brine	propylene glycol	water	water	water	water	ethylene glycol	water	water	water
Total flow rate [l/s]	1.8	1.8	1.8	2.0	1.8	1.8	1.8	1.8	1.8

The simulation was performed using Earth Energy Designer simulation program. There are several outputs of the simulation. First, according to the building heating load, which is the same for all scenarios, the heat flux extracted from the ground can be determined.

Concerning the heat transfer in the ground, different thermal resistances are calculated, including the internal thermal resistance of the borehole, thermal resistance between grouting material and exterior wall of the BHE pipes, thermal resistance of the pipe, the overall resistance between the ground and the brine that circulates inside BHE, as well as the effective borehole resistance. Values obtained for all scenarios are shown in Table 3, together with the Reynolds number values.

Table 3. Thermal resistances obtain from the simulation [$m^2 \cdot K/W$]

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
Internal borehole thermal resistance	0.5171	0.4646	0.3583	0.933	0.2085	0.384	0.3614	0.4197	0.3804
Thermal resistance fluid/ pipe	0.1768	0.0073	0.002	0.0077	0.0106	0.0144	0.0035	0.0127	0.0127
Thermal resistance pipe material	0.0787	0.0775	0.0775	0.176	0.0787	0.0775	0.0775	0.0775	0.0775
Borehole thermal resistance fluid/	0.1885	0.1015	0.0951	0.2285	0.0542	0.1016	0.0959	0.0906	0.1007

ground									
Effective borehole thermal resistance	0.1894	0.1068	0.0954	0.237	0.066	0.1087	0.097	0.114	0.1266
Reynolds number	2,050	9,250	46,251	8,548	5,799	2,845	23,126	4,625	4,625

It is desired to have low thermal resistances in order to increase the heat transfer between the ground and the carrier fluid. For instance, the value of thermal contact resistance between the pipe and the borehole may vary a lot depending on the technique used for pumping the grouting material into the borehole (a good contact is obtained when the filling is made from bottom of the hole to the top of it, otherwise the thermal contact resistance increases).

Also, the heat transfer between the individual pipe/pipes with upward flow and the one/ones with downward flow (for simple U/double U type borehole heat exchanger) is important, thus the internal borehole thermal resistance is calculated.

The value of Reynolds number is important in order to know the type of flow inside the heat exchanger pipes. A laminar flow leads to a poor heat transfer from the pipe wall to the heat carrier fluid.

Also, the series factor of the boreholes connected by one pipeline to the manifold is important because it affects the volume flow rate and thus the power consumption of the circulation pump.

After running the simulation program for all 9 scenarios, the mean fluid temperature that exits from BHE and enters the heat pump evaporator is calculated. Fig. 3 shows its values in the month of January (as being the one having the highest energy demand) of the last year of simulation, as well as in the 10th year (middle of the simulation period), both for the base load and the peak load.

For each scenario, the fluid temperature variation along the last 12 months of the simulation period, meaning the 20th year of operation, is shown in Fig 4.

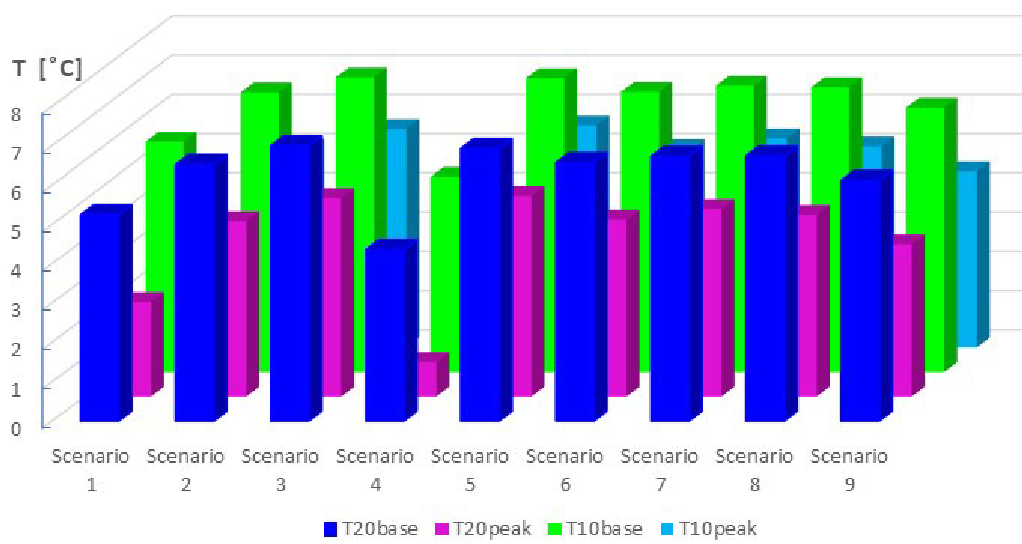

Fig. 3. Mean fluid temperature in January – 10th and 20th year of operation – for base load and peak load

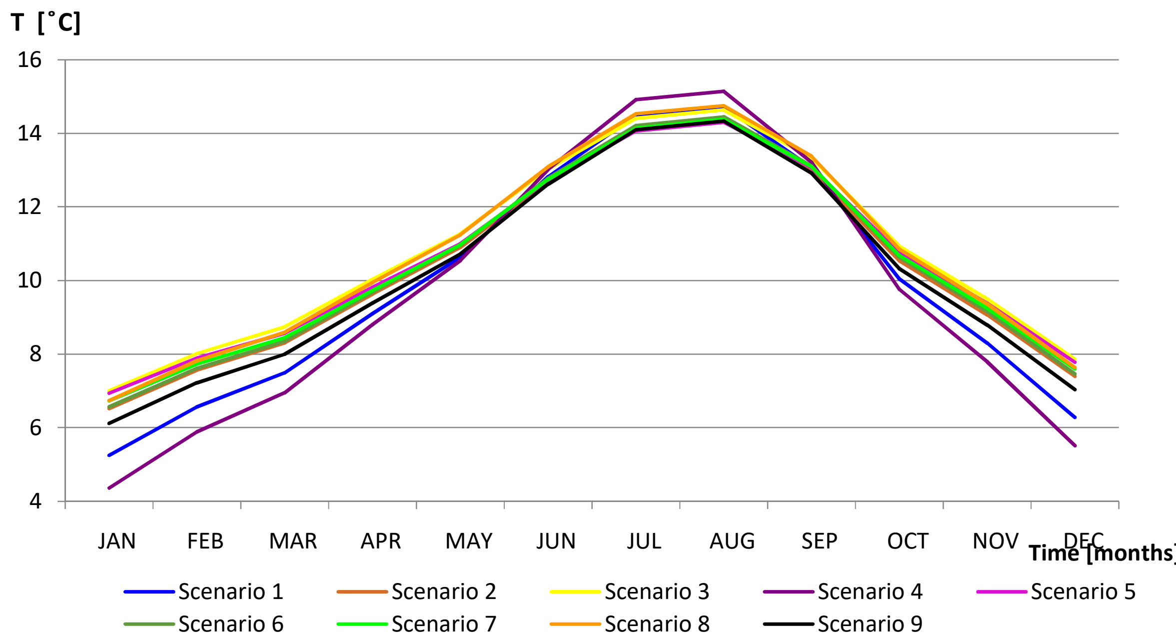

Fig. 4. Mean fluid temperature in the 20th year of operation for base heating load

5. CONCLUSION

The main focus of this study is on heat source sub-system, respectively on the behavior of ground temperature over 20 years of continuous exploitation. For a certain location, one of the most important components of the heat transfer in the ground is the overall borehole thermal resistance. Comparing to the geothermal gradient or to the underground soil composition that determine the ground conductivity, both having a fixed value for a particular location which cannot be influenced, the overall borehole thermal resistance value is based on the comprising thermal resistances which depend on the choices made by the designer and the precision and quality of the grouting operation. But, for an efficient operation of the entire ground coupled heat pump systems, not only the temperature variation over the years for the fluid inside BHE must be considered, also the type of its flow is important.

Different conditions and values for several parameters have been combined and 9 scenarios were set up. For each of them a simulation of the borehole heat exchanger behavior over 20 years was conducted. The following conclusions can be outlined:

- In order to determine the best scenario, not only temperature level is important, but other factors must be considered, too. For instance, the highest mean fluid temperature, after 20 years of continuous operation, is in Scenario 3, but Reynolds number has an extremely big value (>45,000), meaning that the circulation pump of the heat source sub-system requires a much higher power, leading to an increased electric energy consumption and, therefore, to a poor seasonal performance factor (SPF) of the entire GCHP system. The same reasoning may be applied to Scenario 7, where Reynolds number has a value of approx. 23,000. Since mean fluid temperatures in Scenario 8 are very close to those of Scenario 7 and Reynolds number has much better values (less than 5,000), the first has to be chosen.
- Scenario 4 is the worst solution, having the lowest mean fluid temperature. This is due to a very high thermal resistance of BHE pipe and internal resistance. The main problem seems to be at peak loads, where a pronounced cooling of the ground leads to fluid temperatures close to freezing point. This scenario is not at all recommended to be used.
- Scenario 1 shows low mean fluid temperature because two negative effects were cumulated: high borehole internal resistance and very low Reynolds value (2,050) corresponding to a laminar flow. This case is not recommended to be used either.
- A slightly higher value of Reynolds number is shown in Scenario 6, allowing a transitory flow; the borehole internal resistance is among the lowest. Scenario 2 has almost the same mean fluid temperatures, but an increased Reynolds number (approx. 10,000). But both cases have a serial factor of 2, meaning a powerful circulation pump and a lower SPF.
- Scenario 5 shows high mean fluid temperatures and reasonable value of Reynolds number, being the most feasible technical solution.

For the optimum scenario (Scenario 5), the temperature dynamics over the entire operation period is presented in Fig. 5, where both base load and peak load are considered. For both cases, the minimum and the maximum values of temperature are shown.

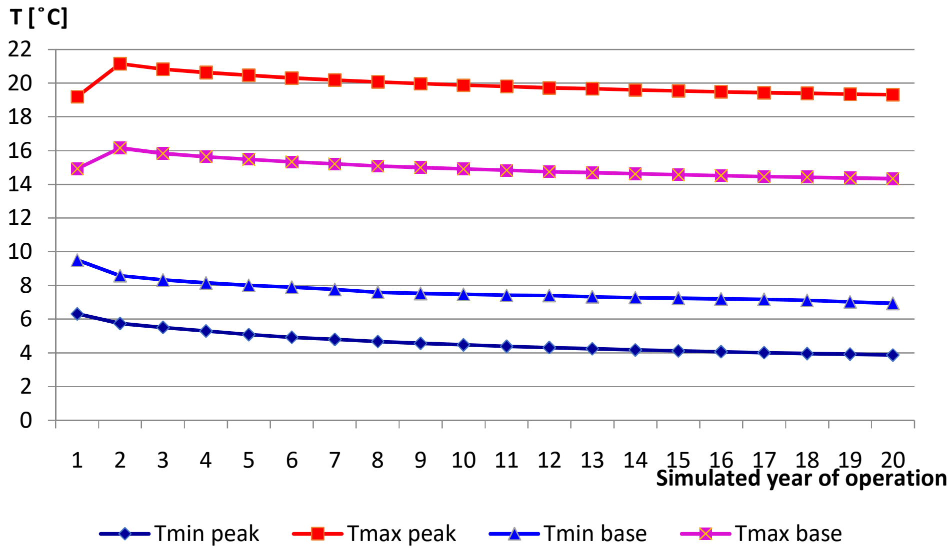

Fig. 5. Fluid temperature variation over 20 years of operation

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