NUMERICAL STUDY ON THERMAL DEPLETION OF THE GROUND AROUND A GEOTHERMAL HEAT PUMP'S PROBE

Constantin IONESCU[1], Clément MONTANGE[2]

Long term use of geothermal heat pumps in heating mode only, thus removing heat from the ground, can lead to cooling of the soil around the probe. This phenomenon leads to decrease of the heat pump performance. This paper presents a numerical study of thermal behaviour of the ground around the probe of a geothermal heat pump that equips a house. This equipment provides heating and partially domestic hot water for an experimental low energy house, built inside the campus of University Politehnica of Bucharest.

Keywords: ground thermal depletion, geothermal heat pump, numerical study

1. Introduction

Globally, 40% of the total world annual energy demand is consumed by buildings [1]. Most of this energy is for the provision of heating, cooling and air conditioning.

The European Directive on Energy Performance of Buildings [2], adopted in May 2010, is the main legal instrument at EU level aiming to improve the energy performance of the buildings. The EU Member States agreed to apply a "Net Zero Energy Program". A net zero-energy building (ZEB) is a building that over a year does not use more energy than it generates. According to this directive, by December 31st 2020, all new buildings must be nearly zero-energy buildings and after December 31st 2018, new buildings occupied and owned by public authorities must be nearly ZEB. Renewable energy sources can be used to achieve these goals. The employment of the renewable energy for space heating leads on one hand to the reduction of primary energy consumption and on the other hand to the reduction of the greenhouse gases emissions.

Taking into account these premises, a new project was developed by the "Politehnica" University of Bucharest. Two low energy houses having a usable surface of 140 m^2 each were built in the campus of the university. One of these houses has the HVAC and the domestic heat water (DHW) preparation systems built around a geothermal heat pump.

[1] Lecturer, Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: cristi.ionescu@energy.pub.ro
[2] Eng., University of Nantes - "Polytech Nantes", France

In last decades, geothermal heat pumps (GHPs) also known as ground source heat pumps have been increased around the world, because they are one of the most energy efficient technologies for providing HVAC and water heating for commercial and residential buildings [3].

A typical GHP system consists of a conventional heat pump unit coupled with single or complex borehole heat exchangers (BHEs).

Long –term heat extraction can cause heat depletion of the ground around the geothermal probe (borehole heat exchanger - BHE). The decrease of the ground temperature depends on soil characteristics, moisture content, building load, initial ground temperature, borehole spacing, etc.

Eugster and Rybach [4] have performed a series of measurements with different operation duration (constant or intermittent heat extraction, different operation/recovery time ratios) for a single 105 m deep BHE used to heat a house in Zurich, Switzerland. Their results shows that the duration of the ground thermal recovery for the studied case roughly equals the duration of the heat extracting operation (e.g. for 30 years of BHE operation are necessary about 30 years to ground thermal recovery).

Trillat-Berdal et. al [5] have studied the thermal discharge from the ground with TRNSYS software, in the case of heat extraction from two boreholes 90 m long at a distance of 10 m. The geothermal probes are double-U type and are coupled with a heat pump that operates 11 h per day, 6 months per year. The results shows that the thermal depletion from the ground is relatively rapid during the first years of heat extraction, and then decreases at an increasingly slower rate, but never achieves a steady state, even after 20 years of operation. The authors noted that the ground temperature difference between the end of the first heating season and after 20 years of operation is of the order of 2 ºC.

This paper presents a numerical study of thermal behaviour of the ground around the probe of a geothermal heat pump that equips an experimental low energy house built inside the campus of University Politehnica of Bucharest. The heat pump provides heating and partially domestic hot water for this house. It is important to know whether the use of heat pump in this case may adversely affect the system operation, in terms of thermal depletion of the ground around the geothermal probe.

2. System description

The HVAC and DHW preparation system installed in the first experimental low-energy house build in the campus of “Politehnica” University of Bucharest is presented in fig. 1. The system functioning can be divided into three distinct periods: winter, summer and off-season.

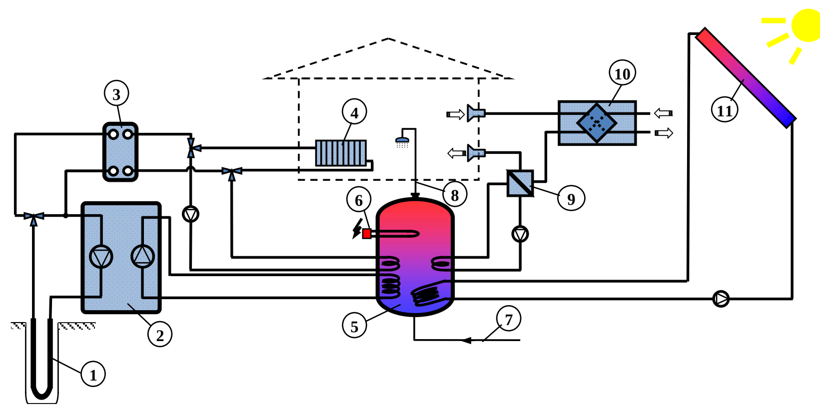

Fig. 1. The HVAC and DHW system of the "Politehnica" experimental low-energy house
1) geothermal heat exchanger; 2) heat pump; 3) passive cooling heat exchanger; 4) radiant panels; 5) hot water tank; 6) electric resistance heater; 7) cold water supply; 8) domestic hot water consumption; 9) water/air heat exchanger; 10) mechanical ventilation heat recovery unit (MVHR); 11) thermal solar panel.

During the *winter*, the heat pump allows the transfer of thermal energy from the ground to the hot water tank inside the house.

The heating of the house is provided by the circulation of hot water in wall-mounted radiant panels. For heating of the water in the hot water tank, there are three separate systems.

The first is a GHP of 5.4 kW thermal load. The geothermal collector of the GHP is closed loop type, made of a vertical double-U probe. The borehole of the GHP collector is of 80 m depth, crossed by water-glycol mixture as heat carrier fluid. Fluid flow in an exchanger of this depth ensures a temperature almost constant throughout the year at heat sink, having as result a good coefficient of performance (COP) [6].

The heat produced by solar collectors on the roof is also stored in the hot water tank. Unfortunately, these solar panels are prone to be hidden by snow in winter so their reliability decreases. In addition, solar panels are oriented so as to allow obtaining a high efficiency when the sun is high in the summer. Their usefulness during the winter is thereby further reduced.

Finally, an electric resistance heater covers heating needs during high consumption periods.

To reduce heat loss due to ventilation, the house is equipped with a mechanical ventilation heat recovery unit (MVHR). The fresh air stream flows in a cross-current direction to the exhaust air, inside the plate heat exchanger of the MVHR unit. The plate heat exchanger saves up to 91% from the exhausted air thermal energy [7]. Before being introduced in the house, the fresh air is further heated using a water-air heat exchanger, to the desired temperature. Ventilation air is heated with hot water taken from the hot water tank.

In the *summer*, the objective of the system is to cool the ventilation air and to provide hot water. In this configuration the GHT is not used, but the flowing of the heat carrier fluid through the geothermal probe is assured for passive cooling. The inside air is cooled with the wall-mounted panels crossed by water cooled in turn by water-glycol mixture circulating through the geothermal probe. To achieve this, a heat exchanger is installed between the circuit of the geothermal exchanger and the circuit of wall panels.

We use again the MVHR unit but this time to cool the incoming fresh air with outgoing exhaust air. The water-air heat exchanger that allows fresh air preheating during the winter is now disconnected.

In this configuration, the solar panels are ideally placed to heat domestic water and the peak needs are provided by electrical resistance.

During the off-season period, when it's not necessary to heat or cool the house, most of the equipments are disconnected. The GHP and also the passive cooling system are off. The MVHR unit remains on to allow the house ventilation. The contributions of solar panels and immersed electric resistances are sufficient to heat the domestic water.

3. Soil cooling study

In connection with the use of a geothermal heat pump over a long period of time, especially on heating mode only, there is a risk of soil cooling. We studied the risk of such a cooling in the context of our geothermal probe. COMSOL software was used to perform various simulations.

3.1. Study conditions evaluation

The soil temperature has a significant variation to a depth of about 8-10 meters, where it stabilizes at a value of about 9.5 ºC [8] followed by a slight increase as we approach the centre of the earth. For this reason our study is made for a depth greater than 8 m.

We simulate the soil studied by a cylinder of internal diameter equal to the diameter of the probe shaft, in our case 0.11 m. The outer diameter of the cylinder must be sufficient so that the ground temperature is no longer affected by the presence of the probe. A study to determine the cylinder radius was conducted. We perform a test for the heat flux delivered and the ground properties we know. The result shows no temperature variation for the cylinder radius greater than 20 m. Soil temperature was set at 9.5 °C.

The soil cooling depends very significantly on its ability to regenerate its internal energy during periods when heat removal from the ground is zero and also when geothermal probe is used in passive-cooling configuration. It is therefore essential to have a good knowledge of the soil properties. The studied soil has the thermal conductivity $\lambda = 1.49$ W.m^{-1}.K^{-1}, the specific heat capacity $c_p = 1.34$ kJ.kg^{-1}.K^{-1} and the density $\rho = 1{,}800$ kg.m^{-3}.

We have simulated the heat removal in the centre of the cylinder by a time variable surface heat flux to come as close to the seasonal heat demand of the heat pump. To calculate the winter consumption we have relied on calculations of heat consumption made during the building design. The design was realized using the December 2009 version of the sizing Excel file PHPP2007. This gave the values of heat demand reported in the table 1. We then divided the demanded heat over the entire surface of the probe and the time for an instantaneous surface heat flux.

Table 1

House heat demand and the surface heat flux of the geothermal probe during winter

	Jan.	Feb.	March	Nov.	Dec.
Heat demand, [kW.h]	609	294	34	211	629
Surface heat flux, [W.m^{-2}]	29.6	15.8	1.65	10.6	30.6

As explained above, the water cooled by the geothermal probe is used during summer to maintain an inside temperature in the comfort domain of 22-26 ºC. We sought to know the value of the equivalent heat flux brought to ground. So we calculated the heat flux removed by circulating cold water in the radiators.

The calculation takes into account that the ventilation air has 0.5 changes/ hour and the thermal efficiency of the MVHR unit is of 91%. In addition, the heat generated by inhabitants, electrical equipments and the solar load is considered.

We set the inside comfort temperature at 22 °C and we use for the heat flux calculus the average temperatures of the soil and air during the period from July to August. We obtain a total heat flux entering the house of 496 W, which must be evacuated to maintain the comfort temperature. This gives a surface heat flux out of the probe of 17.9 W.m^{-2}. This amount of heat is injected into the soil through the radiators and the geothermal probe.

3.2. Study results

In our calculus, we made the assumption that all years are equivalent. Thus, we obtain the heat flux imposed on the inner surface of our cylinder for a determined period of simulation, 10 years in our study (fig. 2).

We then simulated the situation described above for a period of 10 years to have a long-term view of the soil cooling due to the heat pump functioning. We programmed the software to calculate with a time step of one day to have a minimal inaccuracy. The temperature variation issued from simulation is presented with blue color in fig. 3.

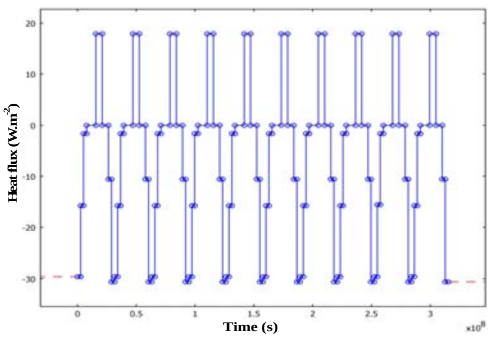

Fig. 2. Variation of heat flux at the ground/probe boundary, over 10 years

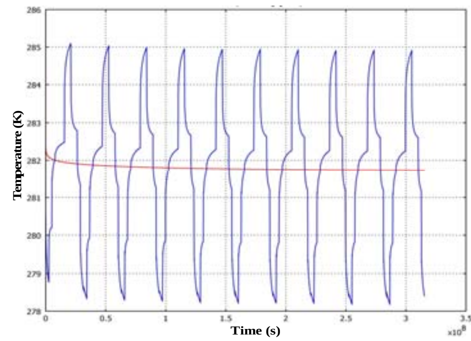

Fig. 3. Comparison of the temperature variation at the probe's contact for an average monthly (blue) and an average annual (red) heat flux

We observe an overall decrease in minimum and maximum values over time, but it is difficult to know precisely the overall decrease in temperature using this method. To solve the difficulty of reading this cooling, we made another simulation. This time we take the average monthly heat fluxes; the heat flow taken over a year has the same value but we avoid the various peaks obtained previously. So we impose a heat flux of 4.29 W.m^{-2} at the inner wall and get the red curve from fig. 3. For a simulation period of 10 years, we obtained a decrease in temperature of about 1 K. The utilization of the average annual heat flow gives a good variation of the temperature at the probe/ground contact. We can therefore use this method to obtain the overall temperature variation at the probe boundary.

We can observe that the evolution of the average temperature follows an almost horizontal asymptote after ten years. We can so therefore seek to determine after how many years the equilibrium temperature is reached. To determine the equilibrium time we perform a simulation with the average annual heat flow over a period of 40 years. Ground temperature becomes almost constant from about 23 years. We can notice that the value obtained for 10 years is very close to the equilibrium temperature since the difference is about 0.01 K.

Another simulation was made to assess the heat pump impact on the ground temperature as we move away from the geothermal collector itself. We observed that the temperature differences caused by the probe are quickly alleviated (fig. 4). We also noted a delay in the heat peak appearance that increases when we move away from the probe.

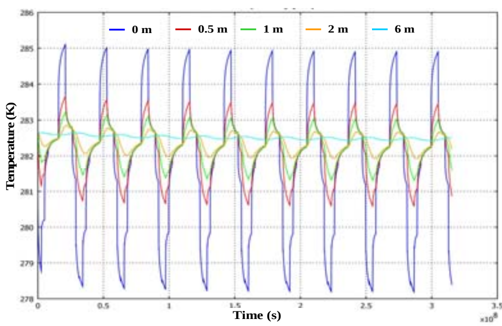

Fig. 4. Ground temperature variation over 10 years for different distances from the probe

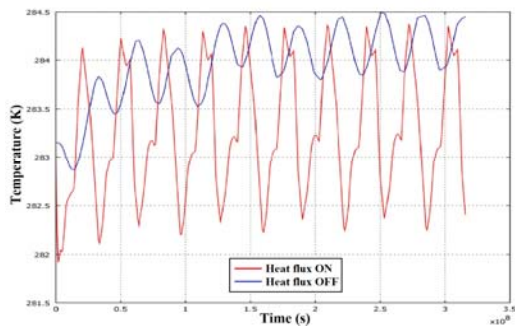

Fig. 5. Ground temperature variation at 8 m depth with and without heat flow from GHP

A significant thermal inertia of the studied soil was also recorded. Thus, the heat pump impact on its environment becomes negligible as soon as we move away for more than a few meters of the collector probe.

3.3. Study of the particular case of the probe's first ten meters

As studies have shown, the ground temperature varies according to season in the first ten meters deep. We will therefore seek to observe the influence of the heat extraction probe on the ground temperature variation for mentioned depth.

In the particular case of the 10 m study, we worked with a 2D axisymmetric simulation rather than a simple 2D simulation.

The heat flux imposed at the probe surface is the same as the one presented in fig. 2. We also imposed a variable temperature at the ground free surface. Average temperatures used are derived from meteorological records.

At first we refined the mesh at the borders, having an imposed heat flow or temperature, but this proved inadequate because we observed significant deformation of the surface temperature. We find that the surface temperature is rough, so it will lead to systematic errors in calculations of temperatures that are influenced by this data. It was therefore necessary to refine the mesh on the entire domain to obtain a valid result. The following studies were therefore conducted with the mesh defined above. An aspect of the performed study is the influence of the geothermal heat pump functioning on the ground temperature evolution. To investigate this phenomenon we compared the temperature variation in both cases: presence and absence of the heat flow generated by the heat pump.

In terms of quality it can be observed that the presence of heat flux due to the heat pump has an impact on the evolution of temperature regardless of the depth. We find that as the depth increases, the presence of the heat flow becomes more important. This makes sense because the distance between the source, which is the outside air, and the study point increases as it moves away from the surface, while the heat flow from the probe is the same since we have assumed it evenly distributed over the entire length of the probe. As example, in fig. 5 is presented the temperature variation at 8 m depth with heat pump on and off.

4. Conclusions

The numerical study presented in the paper shows the thermal behaviour of the ground around the geothermal collector of a heat pump installed in a low energy house built in the campus of the University Politehnica of Bucharest.

For a simulation period of 10 years, we obtained a decrease in temperature of about 1 K. We can observe that the evolution of the average temperature follows an almost horizontal asymptote after ten years.

A significant thermal inertia of the studied soil was also recorded. Thus, the heat pump impact on its environment becomes negligible as soon as we move away from more than a few meters of the collector probe.

A study for the influence of the geothermal heat pump functioning on the ground temperature evolution was also performed. In terms of quality was observed that the presence of heat flux due to the heat pump has an impact on the evolution of temperature regardless of the depth. As the depth increases, the presence of the heat flow becomes more important.

It can be seen that there is no global cooling regardless of the depth. If the number of years does not seem to have any influence on the ground temperature, we find that the depth increasing leads to a decrease in the climate influence.

Acknowledgements

The work has been co-funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/89/1.5/S/62557.

R E F E R E N C E S

[1]. *A.M. Omer*, "Energy, environment and sustainable development", Renewable and Sustainable Energy Reviews, vol. **12**, no. 9, 2008, pp. 2265-2300
[2]. *** Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Official Journal of the European Union
[3]. *J. Lund, B. Sanner, L. Rybach, R. Curtis, G. Hellström*, "Geothermal (ground-source) heat pumps: a world overview", GHC Bulletin, September 2004
[4]. *W.J. Eugster*, *L. Rybach*, "Sustainability of production from borehole heat exchanger fields", Proc. World Geothermal Congres 2000, Kyushu - Tohoku, Japan, May 28 - June 10, 2000
[5]. *V. Trillat-Berdal*, *B. Souyri*, *G. Achard*, "Coupling of geothermal heat pumps with thermal solar collectors", Applied Thermal Engineering, vol. **27**, 2007, pp. 1750-1755
[6]. *J.W. Lund*, "Geothermal Heat Pump Utilization in the United States", Geo-Heat Center Quarterly Bulletin, vol. **11**, no. 1, Geo-Heat Center, Oregon Institute of Technology, 1990
[7]. *** PAUL Wärmerückgewinnung, "Compact Mechanical Ventilation Heat Recovery Unit – Focus 200", Product information, 2010
[8]. *L. Schwartzenberger*, "Maison passive, géothermie et pompe à chaleur", Ed. SAEP, 2008