NUMERICAL STUDY OF THE EVOLUTION OF GROUND-COUPLED HEAT PUMP SYSTEM PERFORMANCE

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ABSTRACT

This study is focused on the ground heat pump (GHP) used in heating single-family houses. These systems generate a ground heat depletion which decreases its performances after several years of operation. The study relates to the evolution of ground heat pumps performances and on simples solutions to maintain a stable temperature in the ground. The use of GHP in cooling mode during the summer and the coupling of thermal solar collectors with the boreholes is a good solution to complete the natural ground recovery. The simulations carried out under TRNSYS show that the benefit exists but is relatively low.

INTRODUCTION

In one century, the greenhouse gas effect concentration has increased by 50 %. In this context, geothermal heat pumps (GHP) with borehole heat exchangers (BHE) are a good solution to decrease the consumption of energy thanks to their high energy efficiency. Low-temperature geothermics are based on the use of the heat contained in the soil via embedded heat exchangers and heat pumps. The ground has a constant temperature throughout the year in a zone ranging between 6 and 46 meters of depth (Chiasson, 1999). This phenomenon results from complex interactions between the heat coming from the surface and the one coming from the depths of the earth. The temperature of this zone corresponds finally to the average temperature of the place considered. Above this zone (depth smaller than 6 m), the temperature of the ground is a function of the climatic conditions; and below (depth larger than 46 meters), the temperature of the ground starts to increase because of the geothermic gradient (2 to 3°C by hm). Heat pumps make usage of this low-temperature energy possible by increasing the outgoing fluid temperature of BHE to values of the order of 35°C, which can be used to heat building directly in a low delivery temperature system such as a heating floor. In these conditions, because the low difference of temperature between the heating floor and the ground, the average value of the performance coefficient (COP of the heat pump) is expected to be above 3. They can also be reversible (heating mode or cooling mode) and thus be used for cooling in the summer. Compared to GHP with borehole heat exchangers, GHP with horizontal heat exchangers are also interesting solutions but they don't offer the same performances. Indeed, they are directly affected by local climatic conditions (Reuss and Sanner, 2000; Bose et Al., 2002) as horizontal heat exchangers are buried at depths between 0.80 and 1.50 m. In addition, the soil surface area occupied by a BHE is very small compared to the one occupied by a horizontal ground heat exchanger. However, it should be pointed out that the cost of boreholes represents the major drawback of the BHE system.

The use of GHP with BHE to heat and/or to cool buildings can create annual imbalances in the ground loads. In the case of heating dominated buildings, a thermal heat depletion of the soil can occur which decreases progressively heat pump entering fluid temperature (EFT). On the contrary, cooling dominated buildings heat the soil, which increases progressively heat pump entering fluid temperature. As a consequence, the coefficient of performance of the heat pump decreases and the installation becomes gradually less interesting.

To avoid this problem, two main solutions are possible. First, the total length of boreholes can be increased, but this is not the more economical solution. Second, hybrid systems can be used. These types of systems incorporate supplementary components, which decrease the thermal load of the boreholes. In the case of cooling dominated buildings, cooling towers are often used to evacuate a part of the heat. This type of installation has received attention in recent years. Yavuzturk (2000) presents some studies concerning these systems which have already been used in buildings since several years (Federal Energy Management Program, 2001). Consequently, we could say that the problem is on its way to be solved for cooling dominated buildings. But for heating dominated building, it is less obvious, as it is more difficult to create than evacuate heat without consuming a considerable amount of energy. A good solution can be the coupling of solar collectors with GHP. Recognition for this type of system has increased since the 1970s oil crisis (Chiasson and Yavuzturk, 2003), but widespread use of the technology has still not been realized.

The majority of existing studies concerning the GHP concern commercial or institutional buildings, which require an important number of boreholes. Studies concerning small GHP systems are scarcer in spite of the important number of individual houses, specialy in France. Indeed, in 2002 in France, according to the INSEE (Institut National de la Statistique et des Etudes Economiques), the proportion of individual houses represent more than half of residential buildings (56 % exactly). In addition, renewable energies offer great prospects for individual houses as demonstrated by the study of another combined heat pump - thermal solar collectors system which has been the subject of a real site experiment in Lugano since 2000 (Pahud et al., 2002).

THE GROUND HEAT DEPLETION

The term "thermal depletion" refers to the decrease in the average soil temperature in the vicinity of the BHE (distance smaller than 10 m). This discharge is generated by extracting heat from the soil. Geothermal heat pump systems are a relatively recent concept, and in spite of an already high number of operational systems in some countries (30 000 in Switzerland), it can still be interesting to study the ground temperature decrease in the long-term, especially for small systems (little number of boreholes) since they are more widespread, particularly for single-family houses.

Eugster and Rybach (2000) conducted measurements on a single, coaxial, 105 m deep BHE used to heat a single family house located in Zurich (Switzerland). The ground temperature at a distance of one meter from the BHE cooled down in the first two years of use. After ten years of use, a new stable thermal equilibrium is established between BHE and ground, at temperatures which are some 2°C lower than originally. However, it is important to note that this study was conducted on a single BHE, resulting in relatively high natural thermal recovery of the ground due to the infinite volume of soil around the BHE. Artificial thermal recovery of the ground is particularly recommended in the case of high concentration of vertical exchangers on the same plot of land (Pahud and Matthey, 2001). In addition, the time to reach a complete thermal recovery depends on how long the BHE has been operational. Principally, the recovery period to reach the initial temperature of the ground equals nearly the operation period (Eugster and Rybach, 2000). But generally, operation time in heating is greater than time of heat recovery. As a consequence, we can say that the natural thermal recovery of the ground is not sufficient to maintain stable performances. Supplementary artificial thermal recovery can be proposed to avoid this defect.

METHODOLOGY FOR SYSTEM SIMULATION AND ANALYSIS

Building description

A 180 m² single family house has been chosen for this study. This house has been constructed during the last two years in Savoie (France). Its photograph is presented in figure 1. This house respects the French thermal regulation (Réglementation Thermique 2000) with a global heat transfer coefficient *Ubat* equal to 0.628 W/(m².K). It consists of a single zone building with one heat pump, two vertical ground heat exchangers (center distance of 10 m) with two double U-pipes and two heating floors (total surface of 154 m²).

Figure 1 View of the house simulated

Borehole length calculation

The required borehole length needs to be calculated for a given load profile. An undersized BHE will lead to unacceptably low (high) inlet temperature in the winter (summer) months. An oversized BHE, on the other hand, while providing safe heat pump operation, may lead to prohibitive installation costs. One common way of sizing ground heat exchangers is to use the methodology for borehole's length calculation proposed by Bernier (2002), which is summarized by equation (1).

$$L = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{(T_g + T_p) - \frac{T_{in,ground} + T_{out,ground}}{2}} \quad (1)$$

where L is the total borehole length required (m).

In the numerator, the variables *qh*, *qm* and *qy* represent the hourly, monthly and yearly values of the ground loads and the variables *R10y*, *R1m*, *R6h* represent effective thermal resistances for ten-years, one-month and six-hours thermal pulse while *Rb* is the effective borehole thermal resistance. The denominator contains four temperatures: the undisturbed ground temperature (*Tg*), a temperature penalty (*Tp*) associated with thermal interference between adjacent bores, and the term (*Tin,ground* + *Tout,ground*)/2 represents the average fluid temperature in boreholes.

Table 1 presents the design values used for the calculation of the total borehole length. In heating mode, the ground loads are given by relation 2.

$$q_{ground\ load} = q_{building\ load} \times \left[1 - \frac{1}{COP_{heat\ pump}}\right] \quad (2)$$

It is assumed that the heating COP of the heat pump is constant at 3.44. This value has been obtained from manufacturer's catalog data of classical heat pump used in residential buildings.

Table 1
Design values used for the total borehole length calculation

Variable	Value
qh	7831 W
qm	4068 W
qy	1618 W
Rb	0.084 m.K/W
R10y	0.132 m.K/W
R1m	0.131 m.K/W
R6h	0.075 m.K/W
Tg	11.6°C
Tp	0°C
Tin,ground	-1°C
Tout,ground	2.2°C
Result : L = 180 m	

To calculate *qh* and *qm*, building design loads are not sufficient and annual hourly energy calculations are required. For our study, the hourly building loads have been obtained in heating mode by simulating the single family house presented previously in the TRNSYS (Klein et al., 2000) modeling environment. The building loads profile is presented on figure 2.

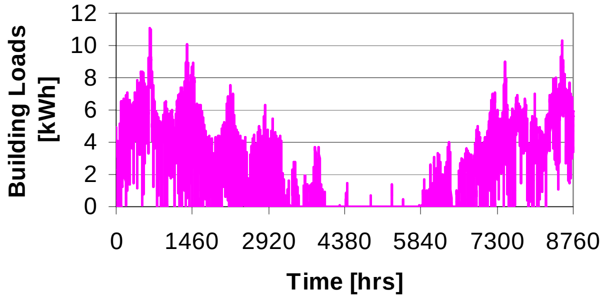

Figure 2 Annual hourly building loads in heating mode for a 20°C indoor temperature considering typical climatic conditions for Chambéry (France)

Model description

The GHP system has been simulated in the TRNSYS modeling environment using standard and nonstandard component models. A schematic of the system is shown in figure 3.

The building is modeled in the TRNSYS environment using Prebid, an interface for creating the building description of the TYPE 56 (multi-zone building). It allows to take into account the real loads of the building whatever time step chosen. Inputs to the type 56 include entering fluid temperature and fluid mass flowrate of the heating floor. Outputs include outgoing fluid temperature. In this way, the model takes into account the behavior of the heating floor, which is necessary to calculate real performances of the heat pump.

Inputs to the heat pump model (TRNSYS component type 668: water to water heat pump) include entering fluid temperatures, fluid mass flowrates and cooling/heating control signal. The model relies on manufacturer's catalog data files containing the heating and cooling capacity and power requirements at different source and load temperatures. Outputs of the model are the outgoing fluid temperatures, the heat pump power and heat transfers to load and from source.

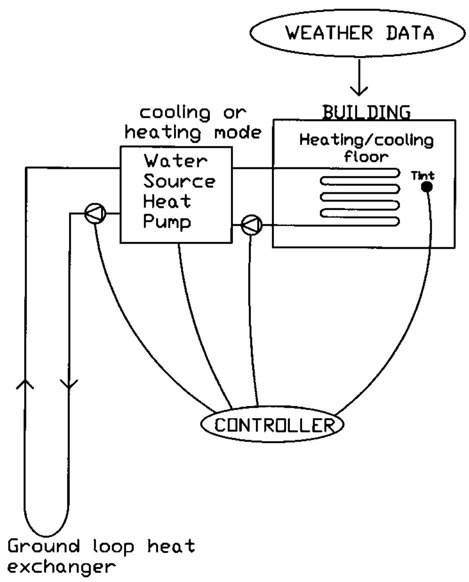

Figure 3 Schematic diagram of the geothermal heat pump system components configuration

Inputs and outputs of the vertical ground loop heat exchanger model (TRNSYS component type 557) include entering and exiting temperatures and fluid mass flowrates. This type uses the duct storage model (DST model) developed at Lund Institute of Technology (LTH) in Sweden (Hellström, 1989) which has been incorporated into TRNSYS by Pahud and Hellström (Pahud et al., 1996). It can be used for the simulation of thermal processes that involve heat and/or cold storage in the ground. The storage volume has the shape of cylinder with vertical symmetry axis. There is convective heat transfer in the ducts and conductive heat transfer in the ground. Three parts represent the temperature in the ground: a global temperature, a local solution, and a steady part. The global and the local problem are solved with use of the explicit finite difference method, whereas the steady part is given by an analytical solution. The total temperature at a point is obtained by a superposition of these three parts.

The controller is simply modeled under TRNSYS by several equations. The circulation of the fluid in the vertical ground heat exchanger and in the heating floor is activated at the same time as the heat pump according to the building's indoor temperature following an on-off controller (TRNSYS component type 2). The controller allows to choose the indoor temperature setting. It is possible to set different temperatures setting during the year, like 20°C for the heating period and 26°C for the cooling period.

RESULTS AND DISCUSSION

Study of the ground heat depletion for use of the GHP in heating mode only

The first part concerns the study of the ground temperature's evolution for the system described in figure 3.

It should be interesting to study the ground temperature evolution when the GHP is only used for heating the building, which signifies that there is no artificial ground thermal recovery. Finally, this theoretical study is comparable with the experimental study carried out by Eugster and Rybach (2000). This first simulation is presented on figure 4 and has been carried out with the following assumptions: setting temperature of 20°C during the heating period, the borehole length (180 m) is dimensioned for this temperature for which the building loads are calculated; each years, the heating period finishes at 2600 hours and starts at 6200 hours; the ground is composed by limestone (thermal conductivity = 2,8 W/(m.K) and volumetric thermal capacity = 2000 kJ/(m^3.K)) which is a typical constitution for the region of Savoie in France. The initial ground temperature is 11.6°C.

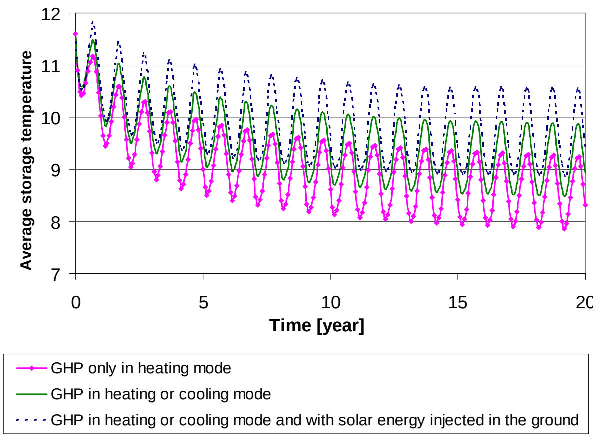

Figure 4 Evolution of the ground storage temperature

Figure 4 shows that the thermal depletion from the ground is relatively fast during the first years of heat extraction, and then evolves at an increasingly slower rate, but never achieves steady state, even after 20 years of operation. If the GHP is only used in heating mode (1825 hours of works per year), the ground temperature difference between the end of the first heating season and after 20 years of operation is of the order of 3°C. Therefore, these results confirm those obtained by Eugster and Rybach (2000).

The diminution of the ground temperature decreases the entering fluid temperature to heat pump, which decreases its coefficient of performance (COP). If the GHP works only in heating mode, the simulations show that the EFT decreases of about 1.75°C between the end of the first year and the end of the twentieth year.

Figure 5 shows the consequences of the ground heat depletion. This figure represents the evolution of the coefficient of performance of the heat pump, which has been obtained with relation 3. As opposed to the entire system's COP, the heat pump's COP, which is presented here, doesn't take into account the pumping energy requirements.

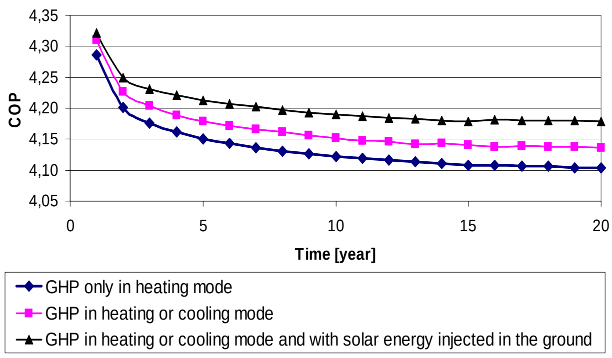

Figure 5 Evolution of the GHP's performances

$$COP = \frac{Q_{YLOAD}}{Q_{YHP}} = \frac{Q_{YLOAD}}{(Q_{YLOAD} - Q_{YLOOP}) / a} \quad (3)$$

where,

Q_{YLOAD} is the yearly production of energy of the heat pump [kWh];

Q_{YLOOP} is the yearly extraction of heat from the ground and used by the heat pump [kWh];

Q_{YHP} is the yearly consumption of the heat pump [kWh];

a is the efficiency of the heat pump's compressor. The value used for our simulations (a =0.97) has been obtained from manufacturer's catalog data.

With the simulation carried out under TRNSYS, Q_{YLOAD} and Q_{YLOOP} are obtained using an integrator (type 24), which integrates for each years of simulation the power (kW) supplied to the heating floor by the heat pump and supplied to the heat pump by the boreholes.

For the assumptions presented previously and if the GHP is only used in heating mode, the performances decrease by about 3.7 % after 20 years of operation. The comparison of figures 4 and 5 shows clearly that the evolutions of the GHP's performances and of the ground temperature are dependent.

We should also discuss the energy consumption (kWh) per m² of building for heating. The compressor of the GHP consumes during the first year 5938 kWh, which represents a ratio of 33 kWh/(m^2.year). During the last year, this consumption increases to 6156 kWh and the ratio to 34.2 kWh/(m2.year), which represents an increasing of more than 3.5 %.

During the heating period, it is also possible that occupants set the indoor temperature to 23°C instead of 20°C, which has been used for the calculation of the building loads and as consequence for the calculation of the required length of boreholes. In this case, the decrease of GHP performance is more important at about 5.6 % and the compressor consumption becomes 46.3 kWh/(m^2.year) the first year and 48.9 kWh/(m^2.year) the last year, which represents an increase of 5.6 %. Obviously, the diminution of performances is more important if occupants don't respect the assumptions used for the design.

As consequences, we may conclude that for a normal use of the system, and for the assumptions presented previously, the heat depletion doesn't result in a very important diminution of GHP performances. Nevertheless, this diminution exists and can be amplified, principally if occupants don't respect the design indoor temperature. In addition, we have looked at a single boreholes configuration, single depth, single ground thermal properties and single load profile. As consequence, additional simulations should be required to study the effect of these parameters on the evolution of the ground heat pump performances.

Relation between the ground heat depletion and the annual heat extraction

In fact, as we can see on figure 6, the diminution of the average storage temperature and consequently the diminution of the performances of the GHP depends directly on the annual heat extraction of the borehole (kWh/m), which is simply calculated using relation 4.

$$\frac{\text{Total heat extraction per year}}{\text{Total length of the boreholes}} \quad (4)$$

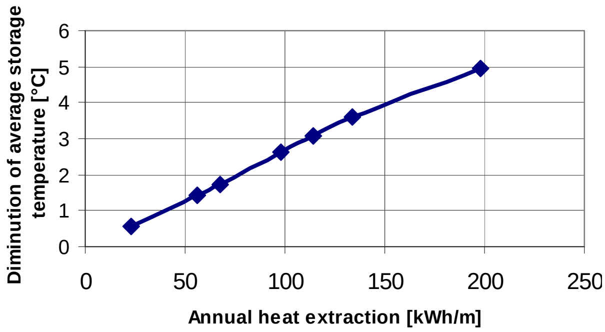

Figure 6 Diminution of the average storage temperature in function of annual heat extraction of the boreholes after 20 years of operation

With the model, the annual heat extraction of the boreholes can be adjusted by modifying the indoor temperature of the house. It is also possible to cool the building during the summer with different temperature settings to decrease the annual heat extraction from the ground. This is the case for the values for which the annual heat extraction is lower than 100 kWh/m.

If the system is only used in heating mode with a setting temperature of 20°C, which corresponds to a normal use of the system, the ground heat depletion is not very important and the annual heat extraction has a value of about 110 kWh/m. This value is valid for our simulation assumptions concerning the ground, i.e. for limestone. We can suppose that for each types of ground, a maximum value of annual ground heat extraction (kWh/m) for which the ground heat depletion is not too important exists.

GHP in cooling mode and coupling of solar collectors with the boreholes

For residential buildings in France, operating time in cooling is not very considerable and is much fewer than operating time in heating. Nevertheless, use of GHP in cooling mode during the summer can be a good solution to complete the natural ground recovery.

An additional solution is the coupling of solar collectors with the boreholes. This hybrid system has been constructed like the diagram presented in figure 7.

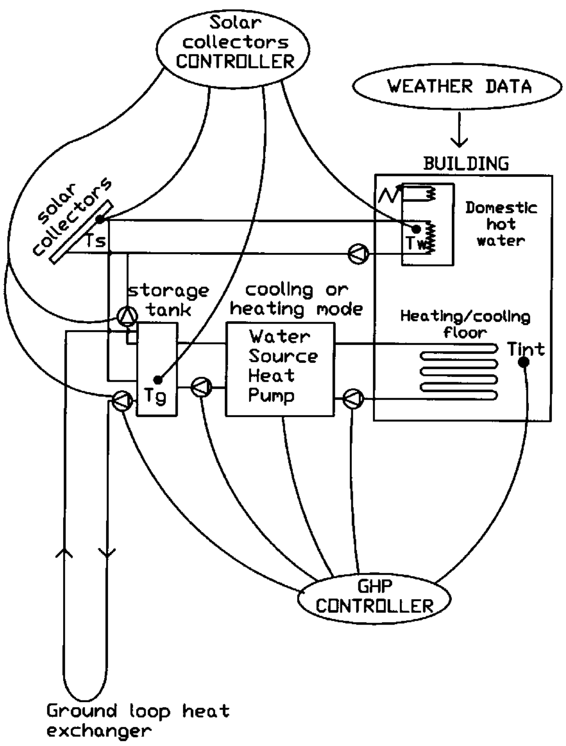

Figure7 Schematic diagram of the coupling of solar collectors with geothermal heat pump system

We can see on figure 7 that the solar collectors are not only used for thermal recharge of the ground. The idea is to produce hot water with the solar collectors and to use them with the boreholes only when the hot water temperature setting is reached. The advantage of this system is that it optimizes operating time of the solar collectors and avoids overheating problems.

Solar collectors, a storage tank of domestic hot water (500 l) and a little storage tank (50 l) have been added to the model used previously.

The type 60 is used to simulate the hot water storage tank and the storage tank between the boreholes and the heat pump. The model takes into account a daily consumption of 175 l (5 occupants) of hot water (55°C) during all the year.

Solar collectors are modeled with a type developed by Plantier and Fraisse (2003). This new TRNSYS TYPE is different from the other solar collector TYPEs, insofar as it takes three important aspects into account: the transient behaviour of the collector, infrared radiation exchanges between cover and surrounding (ground and sky separately), and detailed collector characteristics. The solar collectors surface depends on the hot water needs. For our 175 l/day consumption and for a 500 l storage tank, 6 m^2 can are sufficient. Nevertheless, a simulation has been carried out with a 12 m^2 surface in order to favor the ground thermal recovery.

Figure 8 presents the results of the simulation of the system described in figure 7. The assumptions used are the same as previously (see first part of "results and discussion") and the total borehole length is still 180 m. But 12 m² of solar collectors have been added and the heat pump also works in cooling mode (150 hours of cooling per year at an indoor temperature setting of 26°C).

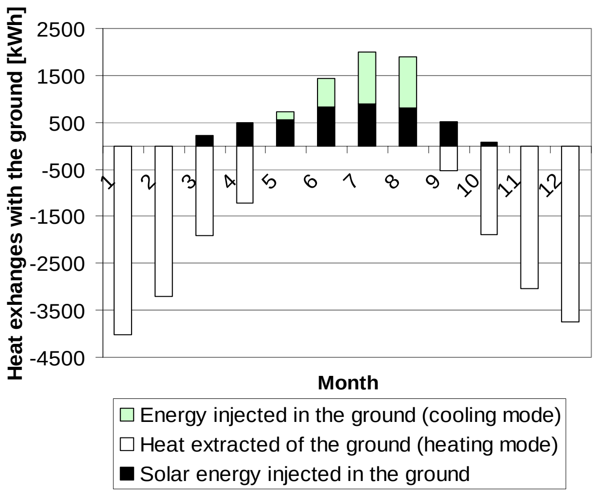

Figure 8 Heat exchanges with the ground during one year, the GHP works in heating or cooling mode and 12 m^2 of solar collectors are coupled with the boreholes

We can see that during the winter solar collectors don't inject heat into the ground. Indeed, during this period, solar energy is totally used to produce hot water. When solar energy becomes sufficient, heat is injected into the ground. For this simulation, 19950 kWh (which corresponds to 110 kWh/m calculated before) are extracted from the ground and 4360 kWh are injected in the ground thanks to the solar collectors. If only 6 m² of solar collectors are used, only 1080 kWh are injected in the ground. It is very much smaller as with this surface the quasi-totality of solar energy is used to heat domestic hot water.

In addition, 2990 kWh are injected in the ground when the heat pump works in cooling mode.

The resulting heat extracted from the ground corresponds to 12600 kWh, which corresponds to 70 kWh/m. As a consequence, the annual heat extraction has decreased by about 40 kWh/m. This new value allows us to say that the annual heat extraction and heat rejection are more balanced.

Indeed, the energy injected represents 37 % of the energy extracted yearly. This better balance results in better performances after several years of operation.

This idea is validated by figure 4 and 5, which also present the evolution of the ground temperature and of the COP if the GHP works in cooling mode and solar collectors are added. If the GHP is used in heating and cooling mode and thermal solar collectors are coupled to the boreholes, the ground temperature difference after 20 years of operation is in the order of 2°C compared to 3°C if no artificial ground heat recovery is generated. In addition, if the GHP works only in heating mode, the EFT decreases by about 1.75°C between the end of the first year and the end of the twentieth year while it decreases by about 0.9°C if the GHP works in cooling mode and solar energy is injected in the ground.

CONCLUSION

Some simulations carried out under TRNSYS to determine the evolution of the performances of GHP have been presented. It concerns heating dominated single-family houses. If the system is correctly designed and used, the ground heat depletion is not too important: the diminution of the average ground temperature is lower than 3°C, and the diminution of entering fluid temperature to the heat pump is about 1.75°C. This has little influence on the evolution of the performances. Indeed, after 20 years of operation in normal conditions, the decrease of performances is about 4 %. This leads to an increase of 1 kWh/(m2.year) of the house heating consumption.

Nevertheless, simple solutions to stabilize the heat pump performances have been studied. First, the GHP can be used in cooling mode to cool the building instead of a traditional cooling system. For the heating dominated single family houses, the operating time in cooling is small but still favors the natural ground heat regeneration by decreasing the annual heat extracted from the boreholes by about 17 kWh/m. Secondly, the coupling of thermal solar collectors used to heat domestic hot water has been studied. Solar energy is injected in the ground only when the setting temperature of the domestic hot water is reached. In order to favor the operation thermal regeneration of the ground, the solar collectors surface can be increased above hot water production requirements. In our simulation, this surface has been doubled (12 m² instead of 6 m²) and the system decreases the yearly extraction of heat from the ground by about 24 kWh/m.

With these two complementary GHP systems, the energy injected in the ground represents 37 % of the energy extracted. As a consequence, the annual imbalance in the ground loads is really reduced which insures better performances after several years of operation even if operating conditions are not optimal.

In addition, the solar recharging of the ground is also an interesting solution to avoid overheating problems associated with solar DHW production. The coupling of solar collectors to underground can also help reduce the necessary borehole length (Chiasson, Yavuzturk, 2003) which can contribute to decrease the initial cost of the system.

ACKNOWLEDGMENT

This study was financially supported by the APS (Assemblée des Pays de Savoie) and by the ADEME (Agence française de l’Environnement et de la Maîtrise de l’Energie) and PUCA (Plan Urbanisme Construction et Architecture) within the scope of proposals for "Energy, environmental and sanitary quality: prepare the Building of 2010".

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