Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Transient Simulation of a Hybrid Ground Source Heat Pump System

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Keywords: Ground Source Heat Pump Systems, Transient Simulation

ABSTRACT

In the last decades, the utilization of the ground thermal energy content represents an attractive alternative for efficient and environmentally sustainable space conditioning, following the outbreak and extensive growth of ground source heat pump systems. Nevertheless, the wider acceptance and development of this technology is largely dependent on the availability of reliable design systems and simulation models that further improve the economic feasibility and sustainable operation of such systems through the accurate design and monitoring of their long-term energy performance.

A hybrid ground source heat pump system that partially covers the heating and cooling demands of a building at National Technical University of Athens Campus in Greece was selected as a case study for the development of an analytical simulation model in the TRNSYS simulation environment. It combines both vertical ground loop heat exchangers and an open loop with flat-plate heat exchangers, utilizing respectively the thermal energy content of the rocks present in the shallow earth adjacent to the building and the thermal energy content of the groundwater.

In the framework of this study, the integrated and analytical modeling of a typical annual operation of the system is presented and the effect of critical design parameters (e.g. heat pump performance characteristics, temperature level control strategies) on its real-time operation and long-term energy performance are further analyzed and discussed. Such an analysis provides the basis for the decoding of the behavior of the system in both transient and steady-state periods of operation, unlike conventional steady-state modeling approaches, setting up dynamic modeling as an invaluable tool for the implementation of realistic ground source heat pump models that can lead to improved design, monitoring and optimization techniques for such systems.

1. INTRODUCTION

Utilisation of low grade thermal energy from the ground is becoming an increasingly popular option for providing highly efficient and environmentally sustainable space conditioning and water heating for both residential and commercial/institutional buildings.

Ground source heat pump (GSHP) systems, which use the ground or groundwater as a heat source/sink, represent attractive alternative to conventional HVAC ones and appear an extensive worldwide growth in recent two decades. The efficiency of GSHP systems is inherently higher than that of air source heat pumps since the heat source/sink maintains a relatively stable temperature throughout the year. Their advantages such as less energy requirements, extended operation during extremely low outside temperatures, higher seasonal COPs and less maintenance needs, have to be compared to the higher initial capital cost due to the extra expense of wells and borehole heat exchangers.

Several approaches have been followed in order to improve the GSHPs economical viability (Bose et al, 2002), as enhancing the system performance, improving the accuracy of the design method and reducing the borehole heat exchangers (BHE) size. In the first case researches have been addressed to the improvement of the heat pump seasonal performance and/or the thermal properties of the various parts of BHEs. As regards the correct design of the system, many efforts have been aimed at the development of both reliable software tools and simpler and more accurate testing procedures for the determination of the ground thermal characteristics. Finally, hybrid configurations have been analysed which can reduce the boreholes size and lower the investment costs of the installations. This is generally performed by limiting the seasonal winter and summer loads imbalance, i.e. inserting heat dissipation devices or systems (such as cooling towers, ponds or aquifers) or auxiliary heating systems (such as solar collectors).

Almost any conventional heating and air-conditioning system may be satisfactorily modelled for energy analysis purposes with a steady-state approach. Ground source heat pump systems including hybrid configurations are a clear exception, as long-term transient heat transfer effects are either neglected or underestimated. Dynamic models for annual and multi-year simulations consequently become an invaluable tool for the design and performance analysis of such systems.

2. DESCRIPTION OF THE SYSTEM

The hybrid ground source heat pump installation under study has been designed to partially cover the heating and cooling demands of a School building at the National Technical University of Athens Campus in Greece. It combines a ground-source with a ground-coupled heat pump system, utilizing the thermal energy content of the groundwater and of the rocks present in the shallow earth adjacent to the building. Two ground source heat pumps (water-to-water) operate in bivalent -heating and cooling- mode with electric energy. The system provides $526kW_{th}$ of heating to the condensers of the heat pumps and $461kW_{th}$ of cooling to the evaporators (CRES and NTUA, 2001). The heating/cooling distribution system into the building consists of dual-speed fan-coil units with maximum supply temperature of 47^oC, while a $5m^3$ vertical cylindrical water tank separates the volume flows inside the heat pumps and the distribution circuit in order to promote the system's operating stability.

More precisely, the ground-source heat pump system utilizes the energy content of the aquifer confined within the Upper Marble formation of Mount Hymettus (from the depth of 200 to 270m) by means of a 280m deep productive borehole yielding an optimum of $35m^3/h$ of groundwater with an average temperature of about 22^oC. The media for heat exchange is a Plate Heat Exchanger (PHE2), with a nominal capacity of 350kW, the primary circuit for which is the major part of the water from the groundwater well, while the secondary circuit is a closed-loop providing energy to the evaporator or condenser of heat pump 2 (HP2). The heating and cooling capacity of HP2 is 328kW and 291kW respectively.

The ground-coupled heat pump system utilizes both the energy content of the aquifer and of the rocks by means of a plate heat exchanger (PHE1), with a nominal capacity of 150kW, and 12 double U-tube borehole heat exchangers (BHES). The water exiting heat pump 1 (HP1) is distributed to the borehole heat exchangers and plate heat exchanger 1 and is mixed just before the entrance to the heat pump. The primary circuit for PHE1 is part of the water from the ground-water well. The heating and cooling capacity of HP1 is 198kW and 170kW respectively. The 12 vertical borehole heat exchangers are each approximately 95m deep, with a 8½" borehole diameter consisting of High Density Polyethylene double U-tubes of Φ32 (HDPE 32mm) backfilled with a mixture of sand, cement and bentonite. The refrigerant medium in our case is water. The vertical borehole heat exchangers provide seasonal ground energy storage as the area of the field acts as a heat source during the heating season and as a heat sink during the cooling season. It should be mentioned that the main reason for the combination of both u-tube and groundwater pumping relies on the fact that the installation at the National Technical University of Athens Campus started as a pilot project for the further research of both closed loop and open loop configurations. In this case, even though effective heat exchange can be achieved through groundwater pumping, through a series of controllers and diverting valves different configurations can be determined leading to useful results for further analysis and research.

A schematic drawing of the total system is shown in Figure 1.

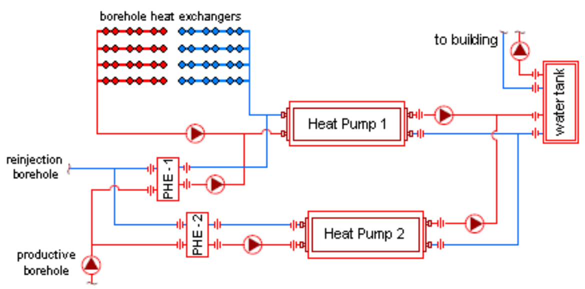

Figure 1: Schematic drawing of the HGSHP system

The geology of the area where the field of the vertical borehole heat exchangers is established can be structured in three layers as follows: The first layer, which reaches a depth of 40m, is characterized by surface alluvial with loose marble conglomerates and clay matrix. The thermal conductivity of this "sand-sandy loam" soil type is relatively small due to its clay content with a value of 1.5W/mK. The second layer is green schist, with thin marble intercalations, and has a 50m thickness. Given its mineral, as well as its density, the thermal conductivity is estimated to 2.6W/mK. The lowest layer starts at 90m below grade and consists of fine grained marble in tectonic contact to the green-schist and extends beyond the maximum well depth. A value of 2.7W/mK is estimated for this layer's thermal conductivity.

3. SYSTEM OPERATION-TRANSIENT ASPECTS

The building at National Technical University of Athens is a 3-storey one with maximum heating and cooling loads of about 1.9×10^6kJ/h and 2.3×10^6kJ/h respectively.

The ground source heat pumps operation in heating and cooling mode is thermostatically controlled in order to meet the desired fan-coils supply temperature. In heating mode an upper temperature set-point of 45^{o}C at the central vertical node of the water storage tank is applied, with a lower dead band in the order of 2^{o}C and 3^{o}C for HP1 and HP2 respectively. In this way HP1 is primarily responsible to raise the fan-coil units supply temperature to the desired set-point, while HP2 operates supportively when needed. In cooling mode a lower set-point temperature of 7^{o}C, with an upper dead band in the order of 2^{o}C and 3^{o}C, controls the operation of HP1 and HP2 respectively. As in heating mode, HP2 starts when the operation of HP1 is insufficient to meet the desired set-point. The operation of the system is characterized by a frequent on/off cycling of the heat pump units and the circulation pumps while, for instance, the borehole heat exchangers operate either under full flow or no flow conditions.

The transient aspects of a ground source heat pump system's operation can have a significant impact on the overall system performance and can cause simulation results to be inaccurate. This is due to measured heat transfer rates or power usage below or above the steady-state values obtained after a short-time period of operation (Hern, 2004). Steady-state models either neglect transient effects or use a degradation factor for the start-up transient. From a designer's perspective, the subsequent cumulative errors that occur in a steady-state approach can lead to a very different design selection than the one that would have been selected using dynamic models (Kummert and Bernier, 2008). In this context, transient modelling can lead to an improved GSHP systems design methodology and provide the basis for the accurate estimation of critical design parameters' effect (e.g. heat pump performance characteristics) on the overall system performance.

4. TRANSIENT SIMULATION OF THE SYSTEM

The simulation of the hybrid ground source heat pump system has been implemented in the TRNSYS simulation environment (Klein et al, 2000). TRNSYS is a transient systems simulation program with a modular structure. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The mathematical models for the subsystem components are given in terms of their ordinary differential or algebraic equations. The modular nature of TRNSYS gives the program tremendous flexibility, and facilitates the addition of mathematical models not included in the standard TRNSYS library. There is a general consensus in the GCHP research community that the DST-TRNSYS combination is probably the best available to perform whole system simulations (Bernier, M., and Randriamiarinjatovo, 2001).

Prior to the development of the simulation model, a 3D model of the building was implemented in Simcad v1.3 (figure 2) and was used as an input to TRNBuild where all thermal zones characteristics (construction materials, infiltration rates, occupancy etc) were defined (figure 3). A building description file (.bui) was created to be used as an input to the TRNSYS simulation environment.

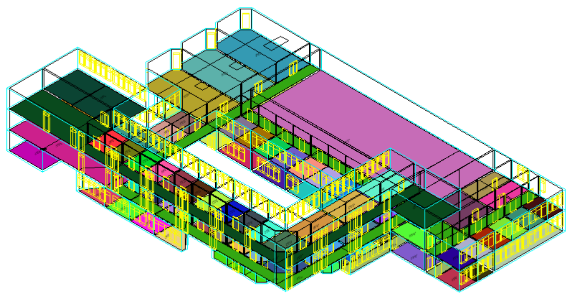

Figure 2: 3D model of the building and its thermal zones in Simcad

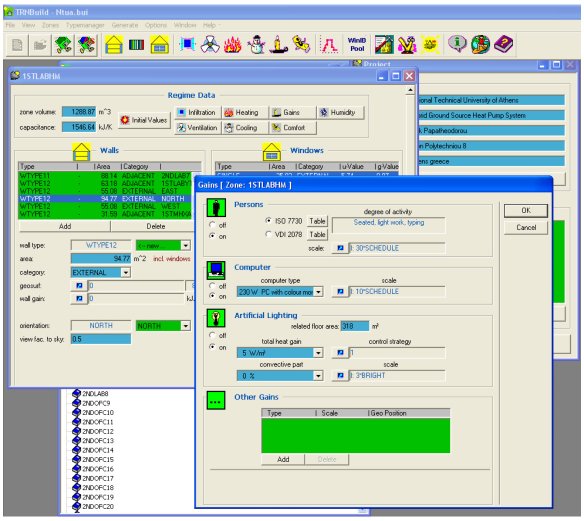

Figure 3: Definition of thermal zones characteristics in TRNbuild

The simulation model developed in TRNSYS (figure 4) is driven using TMY2 weather data for the city of Athens attached to a weather data reader and radiation processor (type 109), while standard differential on/off controller models (type 2), combined with several equations are employed to mimic the thermostatic control scheme of the ground source heat pump units (type 668) and the circulation pumps (type 110).

The building is modeled with type 56 (multi-zone building model), while five stage room thermostats (type 698), with temperature set-points of 20^{o}C and 26^{o}C for heating and cooling respectively and a dead band of 1.5^{o}C, are used to control the building circulation pumps and the dual speed fan-coil units. The latest are implemented through macros in which types 644 (two-speed fan), 753 (heating coil-free floating), 508 (cooling coil-free floating) and 11 (tee pieces, controlled flow mixers) are combined providing, among others, the flow rate, temperature and percent relative humidity of ventilation air distributed to each zone of the building.

The ground source heat pump component model employed in the simulation (type 668) relies on user-supplied data files containing the heating and cooling capacity and power requirements at different source and load temperatures. Inputs to the model include entering fluid temperatures (EFT), fluid mass flow rates and operation control signals, while several outputs such as exiting fluid temperatures (ExFT), heat pump powers (produced by the condenser, absorbed by the evaporator/compressor) and heat transfers to load and from source are obtained.

The field of the vertical borehole heat exchangers is modelled using component type 557 of TRNSYS. 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, 1997). It is well documented, validated and considers multi-bore interactions and long-term effects. The storage volume has a cylindrical shape with rotational symmetry. There is convective heat transfer within the pipes and conductive heat transfer to the storage volume. The temperature of the surrounding ground is calculated, using superposition methods on three parts: a global temperature, a local solution, and a steady-flux solution. The global and local problems are solved with the use of an explicit finite-difference method and the steady-flux solution is obtained analytically. Several parameters are included such as the number of boreholes, the borehole depth and radius, the U-tube configuration and geometry, the grout and ground thermal properties, the type of circulating fluid etc. Inputs and outputs of the vertical ground loop heat exchanger model include EFTs and ExFTs, fluid mass flow rates and heat transfer rates.

Component type 5 (parallel-flow heat exchanger) was employed to model the plate heat exchangers. In this type, given the hot and cold side inlet temperatures and flow rates, the effectiveness is calculated for a fixed value of the overall heat transfer coefficient.

Other components include controlled flow diverters and tee pieces (type 11 instances), and a cylindrical storage tank (type 4a). In this model, the tank is divided into 10 horizontal nodes of equal volume, while the exact inlet and outlet positions for both load and source side are defined.

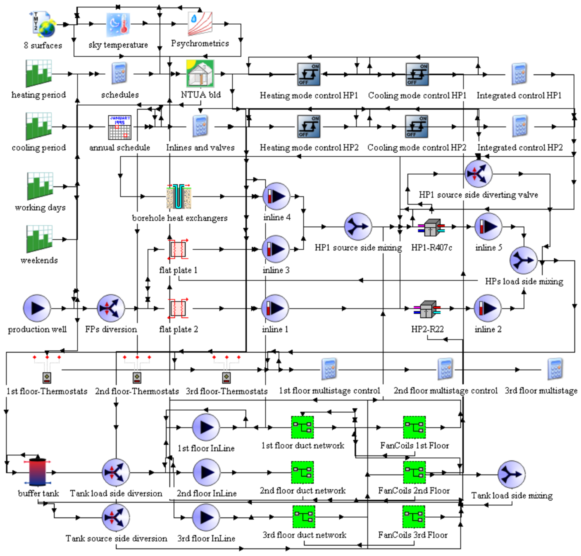

Figure 4: Simulation model of the Hybrid Ground Source Heat Pump System

5. RESULTS AND DISCUSSION

In figure 5, the annual temperature control of one of the thermal zones of the building is illustrated.

In Figure 6, the operation of the hybrid ground source heat pump system for three hours of a typical cooling day where both heat pump units are employed is presented, showing the on/off cycling scheme for the heat pump units as triggered by the storage tank's thermostat.

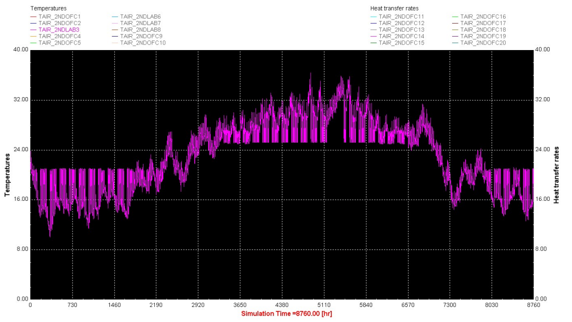

Figure 5: Temperature control of one of the thermal zones of the building

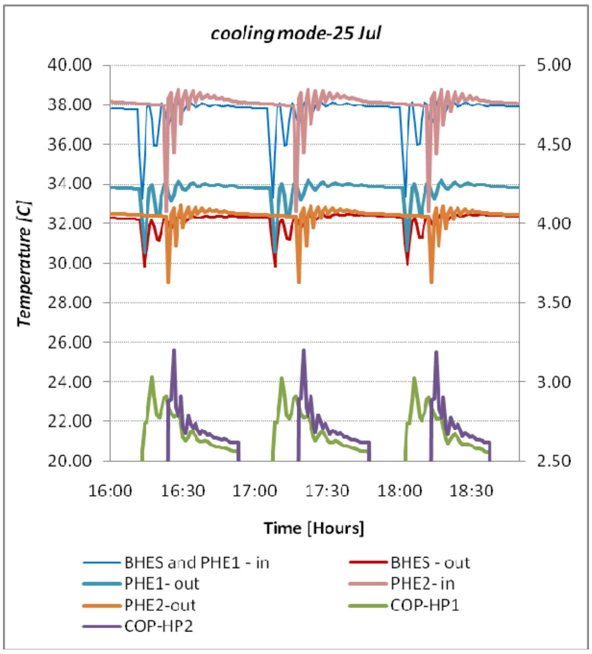

Figure 6: System operation for three hours of a typical cooling day

Heat pump unit 1 is primarily operated at the specified set-point while the rise of the storage tank temperature due to the insufficient operation of HP1 triggers the second heat pump (HP2). Both heat pump units and circulating pumps operate until the set-point temperature of 7^{o}C is reached. Of particular interest is the trend of the COP for both heat pump units during their operation. As clearly depicted in figure 6, the lower the difference between inlet source and outlet load temperatures, i.e. the energy which needs to be added through compression, the higher the COP. As HP1 insufficiently operates, the temperature of the water entering both the load and source side increases. The subsequent high temperature differential for the first transient minutes of operation increases the power drawn by the heat pump compressor. The operation of HP2 leads to the rapid decrease of the storage tank temperature and therefore the temperature entering the load side of both heat pump units. The COP value of HP1 is further decreased while the simultaneous temperature rise on the source side of HP2 leads to decreasing COP values as well.

In figure 7, the operation of the hybrid ground source heat pump system for one hour of a typical heating day where both heat pump units are simultaneously employed is presented.

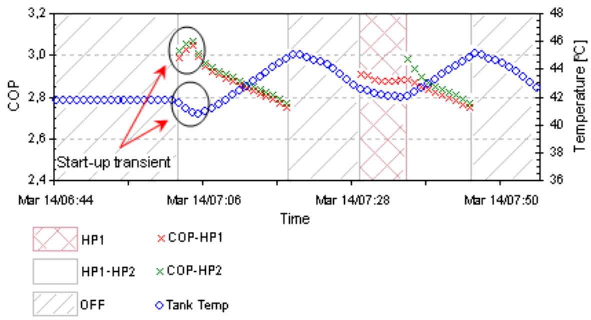

Figure 7: System operation for one hour of a typical heating day

Both heat pumps are triggered by the heating time schedule (7am-7pm) and the thermostatic control scheme applied. Upon heat pumps start-up, water that has been stagnated in the pipes for over twelve hours is pumped into the tank resulting in an initial drop of its temperature. Once this water is well mixed with the tank water, the entire tank is quickly heated. When the temperature reaches the specified set-point, the heat pump units are turned off. HP1 is again triggered at about 43^{o}C, while if its operation is insufficient to raise the storage tank's temperature, as for the period presented, HP2 is employed at about 42^{o}C in order for the desired set-point temperature to be met. A significantly interesting trend is the rise of the COP of both heat pump units for the first minutes since start-up. This is due to the long pipe distance that the water circulated back to the heat pumps has to travel.

The transient response periods during start-ups for two hours of a typical heating day, are clearly shown in figure 8.

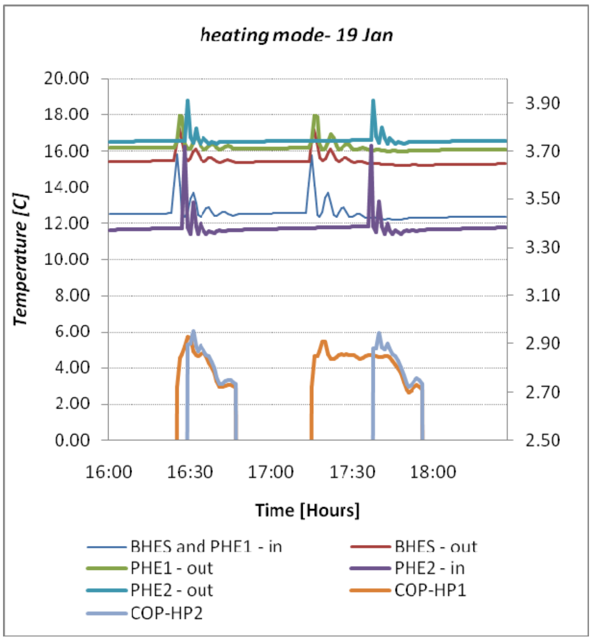

Figure 8: System operation for three hours of a typical cooling day

Figures 9 and 10 demonstrate the monthly heat transfer rates for the field of borehole heat exchangers, PHE1 and PHE2 for an annual operation of the system.

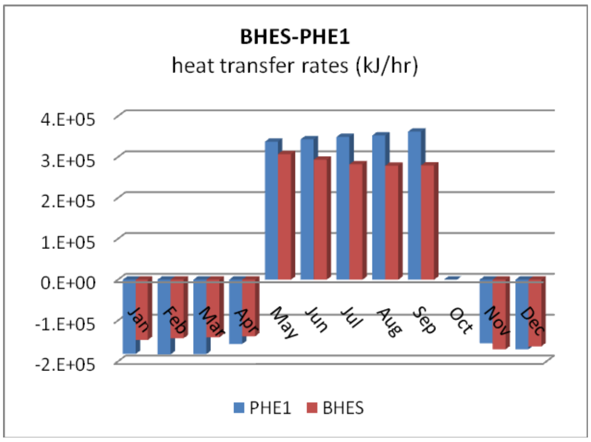

Figure 9: Monthly heat transfer rates on BHES and PHE1

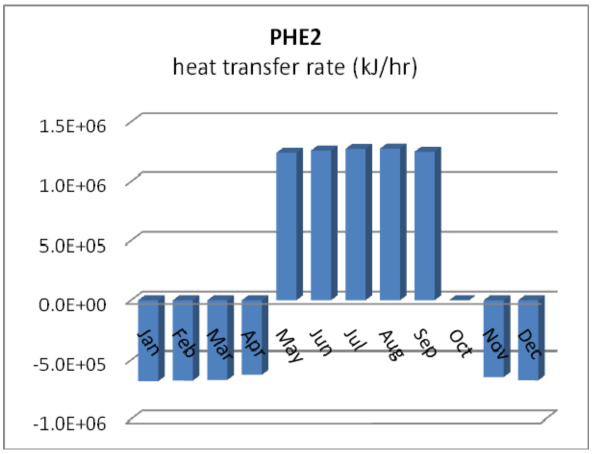

Figure 10: Monthly heat transfer rates on PHE2

In heating mode, the operation of HP1 is achieved by the heat transfer of about $100kW_{th}$ or 360,000kJ/h at near steady-state conditions. Approximately $45kW_{th}$ are obtained from the energy influx from the borehole heat exchangers and $55kW_{th}$ from the secondary circuit of PHE1, providing the necessary energy for the operation of the evaporator of the heat pump. The respective amount of thermal energy provided to the evaporator of HP2 through the secondary circuit of PHE2 is approximately $195kW_{th}$.

In cooling mode, at near steady-state conditions the earth is furnished with approximately $200kW_{th}$ or 720,000kJ/h of thermal energy from the condenser of heat pump 1 with a 55-45 percent distribution through PHE1 and the BHES respectively. In the case of HP2, approximately $375kW_{th}$ or $1.35x10^6$kJ/h is provided to the groundwater through PHE2 at near steady-state conditions.

The monthly running hours and energy consumption of each heat pump unit are presented in figures 11-14.

The annual running periods in heating/cooling mode are in the order of 572/796 hours for HP1 and 308/478 hours for HP2.

The trends of thermal depletion and recovery for both ground and groundwater, as well as of the energy transferred on the load side of the heat pumps are clearly depicted in figures 15 and 16.

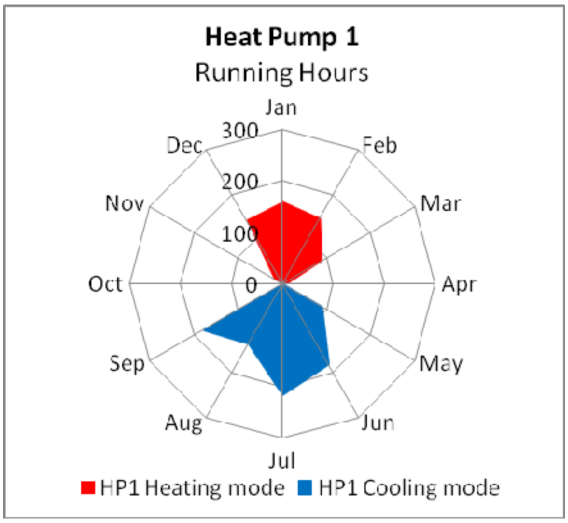

Figure 11: Monthly Running Hours of HP1

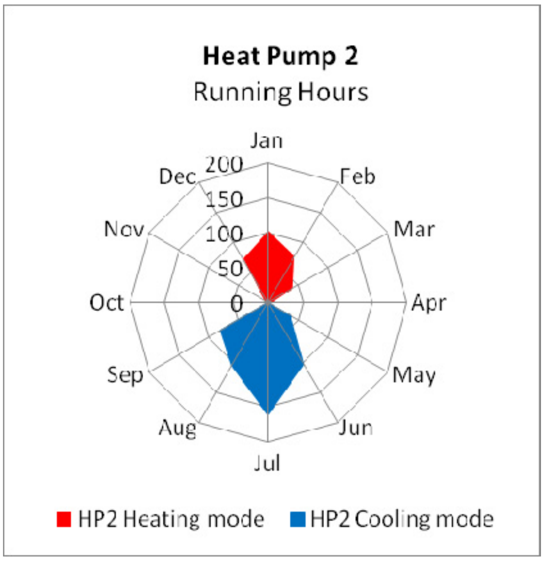

Figure 12: Monthly Running Hours of HP2

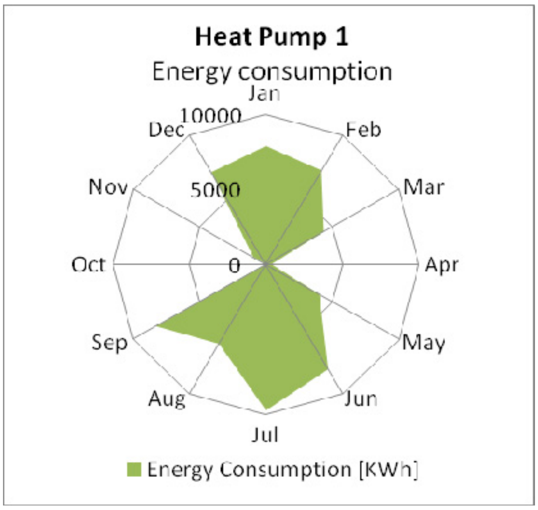

Figure 13: Monthly Energy Consumption of HP1

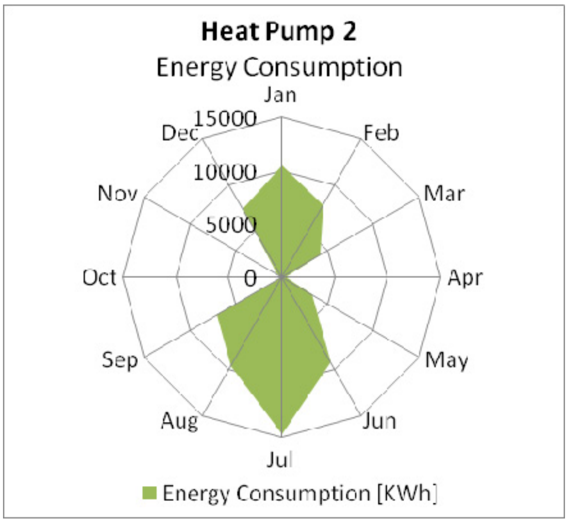

Figure 14: Monthly Energy Consumption of HP2

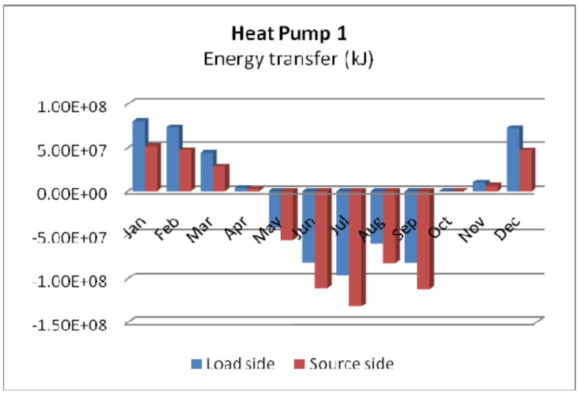

Figure 15: Monthly Energy Transfer on Source and Load side of Heat Pump 1

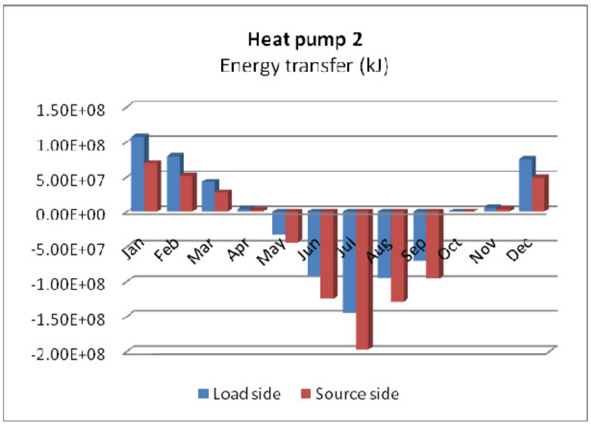

Figure 16: Monthly Energy Transfer on Source and Load side of Heat Pump 2

The variation of the average soil temperature in the vicinity of the BHES field was also studied since an extensive thermal depletion of the soil may result in a decrease of the seasonal performance factor of the system and thus render its long-term operation uncertain (Berdal et al, 2007). As shown in figure 17, a rise in the order of 0.4°C for the average soil temperature is observed after an annual operation of the system. However, the hybrid configuration of the system provides the option of different operation/recovery time ratios in order to maintain effective heat extraction at the field of the borehole heat exchangers.

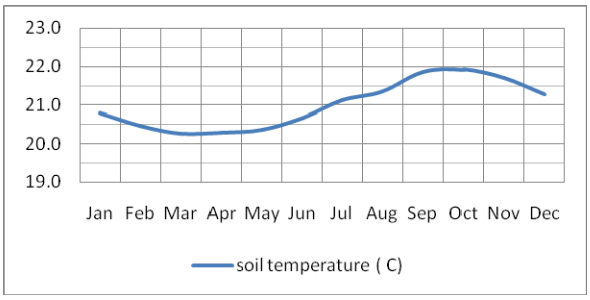

Figure 17: Soil temperature variation in the vicinity of the borehole heat exchangers field

6. CONCLUSIONS

Integrated and analytical modelling of all aspects involved in a complex hybrid ground source heat pump system which combines a field of borehole heat exchangers, a groundwater loop and plate heat exchangers was presented.

The simulation covered a typical annual operation of the system for the heating and cooling of a University building in Athens, Greece, providing accurate predictions of the expected temperature levels, heat transfer rates and energy use on both transient and steady-state operating periods.

The results obtained support the general consensus that transient simulation can prove to be a very reliable approach for the evaluation of the real-time operation and long-term energy performance of ground source heat pump systems.

From a designer's perspective, transient modelling can lead to an improved GSHP systems design methodology and provide the basis for the accurate estimation of critical design parameters' effect on the overall system performance.

ACKNOWLEDGEMENTS

This work has been funded by the project PENED 2003. The project is co financed 75% of public expenditure through EC - European Social Fund, 25% of public expenditure through Ministry of Development - General Secretariat of Research and Technology and through private sector, under measure 8.3 of OPERATIONAL PROGRAMME "COMPETITIVENESS" in the 3rd Community Support Programme.

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