International Scientific Journal
Environmental Science
http://environment.scientific-journal.com

Implementing the GEOPEAK Project in Greece towards the achievement of Europe 20-20-20 targets: Development and Evaluation of a Geothermal Heat Pump of High Efficiency

M.Gr. Vrachopoulos, M.K. Koukou, N. Tachos, S. Kalognomos, A. Adamidis, F. Lavrenti, J. Pappas, P. Xygogianni
Energy and Environmental Research Laboratory,
Mechanical Engineering Department
Central Greece University of Applied Sciences
344 00 Psachna, Evia, Greece mvrachop@gmail.com

C.Karytsas
Center for Renewable Energy Sources and Saving (CRES)
19o Km Marathonos Ave, 19009, Pikermi Attiki Greece
e-mail: kkari@cres.gr

***Abstract*— In "GEOPEAK" project the development and evaluation of the first Greek geothermal heat pump is achieved in an integrated way. Six geothermal heat pumps of various capacities with a high coefficient of performance (COP) have been developed. Experimental evaluation has been performed on those prototypes at the one of the project partners INTERKLIMA's test lab. Three borehole heat exchangers (BHEs) have been developed at Central Greece University of Applied Sciences campus at Evia island and during the next period they will be connected with one of the prototypes to test its performance at real conditions. This system will cover cooling and heating needs in one of the university buildings and by this way it will operate in real conditions and environment. Simulation work is also carried out both for the evaluation of heat pump's performance and analysis of BHEs so as to develop tools for design and optimization purposes. In this work, results from the BHEs modeling are presented and discussed. The developed model predicts realistically the BHE behavior and it can be used as a tool for design and optimization purposes.**

Keywords—borehole geothermal heat exchanger; heat pump;

I. Introduction

Geothermal heat pump or ground-source heat pump systems (GSHP) that use shallow geothermal energy resources for heating and cooling purposes have been popular throughout the world [1]. According to GSHP Market development in Greece Action Plan [2] the country's target is to meet the EU heating and cooling RES targets ~580 GWh by 2020, through the installation of new GSHP systems. This corresponds to an installed GSHP capacity of 265 MW with a technology mix share of 45% closed, 40% open and 15% horizontal systems [2,3]. The market for such systems that exploit swallow geothermal energy for heating/cooling and hot water for use in buildings, offices, hotels, etc is based on a quite mature and tested technology. As it is depicted from the results of projects of DG TREN the COP of geothermal heat pumps may be improved [4,5]. The wide spread of the GSHP technology during the last twenty years has been attributed to the fact that their application saves energy about 50% if it is compared with traditional ways used for heating, cooling and production of hot water for use (e.g. natural gas). Simultaneously, the primary energy saving in comparison with that achieved using conventional means (e.g. natural gas) is about 30-40% with a respective decrease of pollutant emission to the atmosphere. A basic parameter for the achieved energy saving through the use of GSHP technology is COP (Coefficient of Performance) defined as the ratio of the produced thermal energy in kWth to the consumption of electrical energy in kWe. The better the heat pump efficiency the higher is the COP thus energy saving is higher. For most of the GSHPs in the market COP ranges from 4.5 to 5.5. In GROUNDHIT project [4] a geothermal heat pump with a COP 6.06 has been developed when the COP for similar systems under the same conditions is 5.40. In Greece because of the recent favourable legislative framework an increase of the new installed geothermal heat pumps by 100% to 120% per year has been taken place. The latter are confirmed by EGEC data forecasting 30000 installed GHSPs until 2020. Unfortunately, all the hydro cooled geothermal heat pumps are imported from USA, Germany, France, Austria and Sweden resulting in financial loss for Greece of about 5.000.000 € for the period 2006-2008. Because of the predicted increase in GSHP sales until 2020 the financial loss will increase to 50.000.000 € per year. The GEOPEAK project through the development of the first Greek geothermal heat pump will contribute to the decrease of that loss as it will cover 25% of the annual needs for GSHP systems.

Work in the project comprises experimental development and measurements at laboratory and real conditions to evaluate the GSHP performance and modeling work to assist system optimization and performance analysis. Experimental work includes test of the GSHPs at certain conditions at one of the partner's lab and development of a BHE installation at the Central Greece University of Applied Sciences campus to continue tests at real conditions. Modeling work includes simulation of the heat pump performance and development of a BHE model to account for the various parameters that influence the system operation. In this work, results from the BHE modeling are presented and discussed.

In the literature, there are numerous modeling studies on the design and performance of BHEs [6-9]. However, there are limited studies for Greece where the soil temperature is stable in most areas and suitable for such applications. The assessment procedure for the BHE design requires an understanding and corresponding treatment of the physical processes in and around it. In the cooling season, the heat of indoor air is delivered by a heat pump to circulating fluid. The circulating fluid transports heat through a U-tube by convection, and transports the heat to the ground by conduction. The conducted heat raises the temperature of the ground or/and groundwater. The opposite process occurs in the heating season. The BHE size plays a decisive role on the operation performance of the GSHP system thus it is of great importance to work out sophisticated and validated tools by which the thermal behavior of any GSHP system can be assessed.

II. About GeoPeak project

The main objective of this project is the development of six (6) geothermal heat pumps (capacity 15, 20, 30, 40, 60 and 80 kW) with a high performance coefficient. Experimental and laboratory test operations will be performed using the above prototypes. The first test has been accomplished at INTERKLIMA labs and the final one is currently conducted at Central Greece University of Applied Sciences campus at Psachna Evia. For that purpose, three borehole heat exchangers have been manufactured at the campus and they will be connected with one of the prototypes (Fig. 1). By this way the prototype will operate in real conditions and environment. The final design of the six (6) geothermal heat pumps will be completed after the evaluation of the results in laboratory and real operation.

Fig. 1. View of GSHP.

In laboratory tests it was necessary to develop water temperatures for the evaporator side similar to ground temperatures and for the condenser side temperatures similar to building temperatures. For the first case, an existing hydraulic circuit has been customized with water feed rate and temperature control. For the condenser side a pump with water variable feed rate was used in connection with a storage tank and a central air conditioning unit of variable air feed rate. During GSHP tests the following parameters or quantities were recorded and evaluated: inlet and outlet temperatures of cooling medium at condenser, inlet and outlet temperatures of water at condenser, inlet and outlet temperatures of water at evaporator, water feed rate at condenser and evaporator, absorbed power, voltage, current intensity, COP. Based on detail simulations it was decided to use scroll compressors of high efficiency and plate type heat exchangers (cooling medium-water) adequate for operation with R410A. The system design has been reviewed and it was realized that only increase of heat exchanger surface may assure better results as the expansion device is very accurate because of electronic control. The design temperatures in the condenser are those of the low temperature heating system (floor heating or fan coil) inside the building (Table I). The temperatures at the evaporator side were chosen in order to serve open and closed loop systems. Typical results indicate a COP of 5.38 for Eurovent floor heating conditions for the heat pump of 15kW to 5.82 for that of 60kW at the same conditions.

TABLE I. TYPICAL TEST CONDITIONS FROM MEASUREMENTS OF HEAT PUMPS EFFICIENCY

	$T_{in\ evap}$	$T_{out\ evap}$	$T_{in\ cond}$	$T_{out\ cond}$
Heating (Eurovent-floor heating)	10^oC	7^oC	30^oC	35^oC
Heating (Eurovent-Fan Coil)	10^oC	7^oC	40^oC	45^oC
Heating (Low temperature Fan coil)	10^oC	7^oC	35^oC	40^oC

III. The borehole installations

A. Boreholes description – Study area

A system consisted of a closed circuit of vertical borehole heat exchangers for the exploitation of swallow geothermal energy has been developed at Central Greece University of Applied Sciences campus at Psachna Evia island (Fig. 2).

Fig. 2. Area of boreholes placement.

Three boreholes with a total length of 240m have been constructed and a pair of U-type geothermal heat exchangers has been put inside each of them (production boreholes). Furthermore, two vertical boreholes each 60m depth have been developed (measurement boreholes) at a distance shown in Fig. 3.

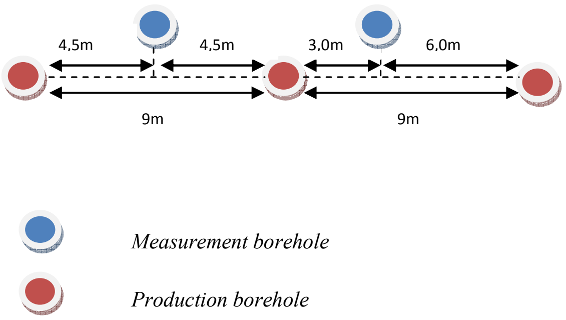
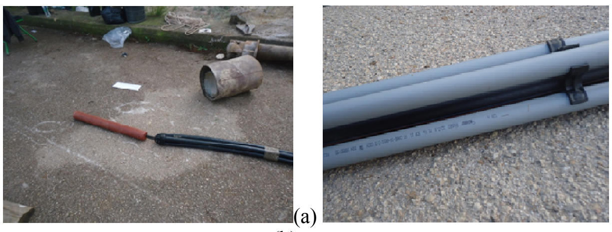


Fig. 3. Distance between boreholes

The vertical geothermal networks are made of PEXa or PE Φ32x2.9mm. Other components include: i. a steel weight of 25kg with cylindrical shape and 80mm diameter (Fig. 4a) that has been adapted to the base of the pair of the U-type heat exchangers which is used to facilitate the introduction of the tubes inside boreholes, ii. Distance holders 10x32mm made of high density polyethylene PE-100 (Fig. 4b) located per 5m scanning all the U-type tubes length which are used to support the right position of tubes inside the boreholes.



(a)
(b)

Fig. 4. a) steel weight adapted ath U-type pair of tubes b) Distance holder

Fig. 5. Introduction of geothermal heat exchanger in the borehole.

The diameter of each borehole is 8in till 3m of depth and $6^{1/2}$ in deeper. The boreholes, after the insertion of U-tube, were backfilled with grout in order to ensure good thermal contactivity with the ground. The grout used to fill the boreholes consisted of sand and a mixture of 70% cement and 30% betonite. However, as it was found aquiferus at 42m depth below this depth instead of grout sand was used to fill the rest of the boreholes.

B. *Climatic Data*

Table II shows the climatic conditions, together with the heating degree days at the area studied. The values of the ambient air temperatures, relative humidity are based on measurements for Chalkida town which is very close to the campus area [7].

TABLE II. CLIMATIC DATA [7]

	Average monthly temperature	Average max monthly temperature	Average min monthly temperature	Average mean relative humidity	Heating DD
	°C	*°C*	*°C*	*(%)*	
Jan	9,1	12,7	5,2	73,4	276
Feb	9,1	12,4	5,1	71,8	249
Mar	11,8	14,8	6,9	69,8	192
Apr	16,1	18,6	9,9	63,5	57
May	20,7	22,6	14,3	60,2	-
Jun	25,8	27,4	18,9	54,6	-
Jul	27,8	30,7	21,4	53,1	-
Aug	27,5	30,3	21,5	55,0	-
Sep	24,5	27,0	17,9	58,2	-
Oct	19,7	21,0	14,4	67,5	-
Nov	13,9	16,0	9,9	74,7	123
Dec	10,5	13,9	6,6	75,3	233

C. *Soil Properties-Geological data*

The transfer of heat between the borehole heat exchanger and adjoining soil is primarily by heat conduction. It depends strongly on the soil type, temperature gradients. Soil properties namely, thermal conductivity k, density ρ and specific heat capacity C_p must be known or estimated to predict the thermal behavior (Table 1).

TABLE III. SOIL PROPERTIES AT VARIOUS DEPTHS

	0-42m	***42-70m***	***70-80m***
Thermal conductivity (W/mK)	1,97	2,03	2,58
Density (kg/m^3)	1855	2110	2538
Specific heat capacity (J/kgK)	800	1460	1048
Porosity (%)	30	35	10

The relief of the territory of Psachna is described as of middle intensity. Altitude is up to 164m. The sedimentary plain of Psachna is consisted by torrential alluvium of

Messapia stream. The geological structure of the study area is consisted from lower to deeper of:

- Terrestrial formations: red coloured silty clay soil with conglomerates, gravels interstratified
- Transgretional limestone: two layers are detected at the Upper Cretaceous and Lower Cretaceous. The Upper layer formatted by grey fine-midbeded till lamellar limestone with interstratified nodules and pyrites. Layer thickness up to 100m. In a few places appears disaccordance between upper and lower layer of limestone.

In Fig. 6 geological details for one of the production boreholes is shown.

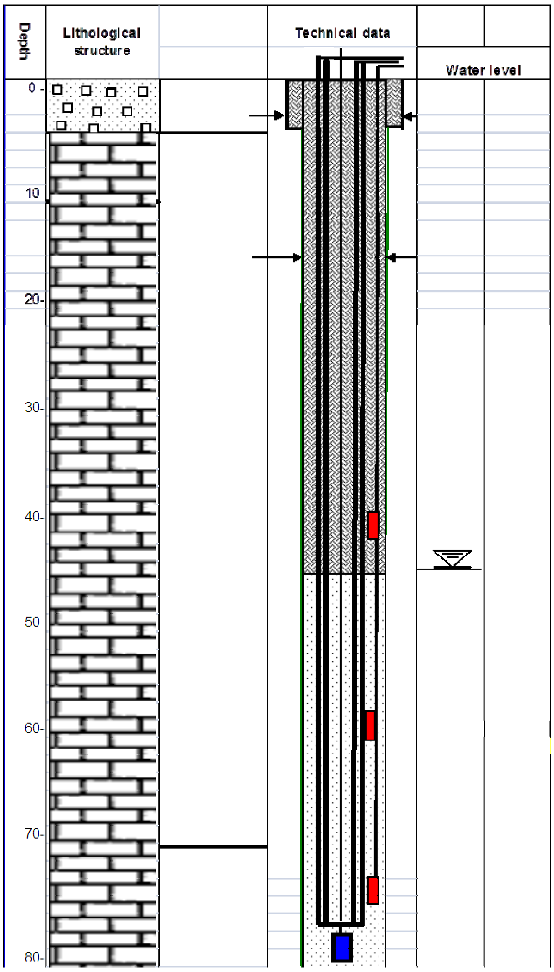


Fig. 6. Borehole section

D. Measurement equipment

In BHEs 17 thermocouples of type T were installed (3 in each of the production boreholes and four in each of the measurement boreholes). The thermocouples will be connected through collectors with the GSHP. They are also connected with a NI data logger to monitor the temperatures of the boreholes. Flow meters have also been installed at selected network points. The data logger was programmed by means of the Labview software. Measurements were recorded on a daily basis using the same software. The equipment was properly calibrated prior to the test.

IV. Simulating a borehole heat exchanger

A. Model description

This model/algorithm simulates the transient phenomenon of heat transfer in a pair of vertical U-type geothermal heat exchangers. The model couples the equations of the 1D mesh of the double U-tube with the equations of the 2D polar mesh of the ground, in order to find the temperatures at the nodes for each time step. For each time step the developed algorithm solves sequentially two sets of equations. The first set (Eqs. 1,2) calculates the temperatures along the BHE length, first at the input section and then at the output/return section of the BHE. It is assumed that the temperature at its inlet is known (Fig. 7). Temperatures at the neighborhood (ground) of the BHE are also provided by the solution of Eq. 3. The second set of equation (Eq. 3) is solved to find temperatures at the grid nodes knowing their values at the previous time step. Before the solution of that equation, temperatures at BHE nodes are refreshed taking the average value of the temperature at the external surface of input section and the temperature at the external surface of output/return section. By this way, transient heat transfer between BHE and ground is simulated.

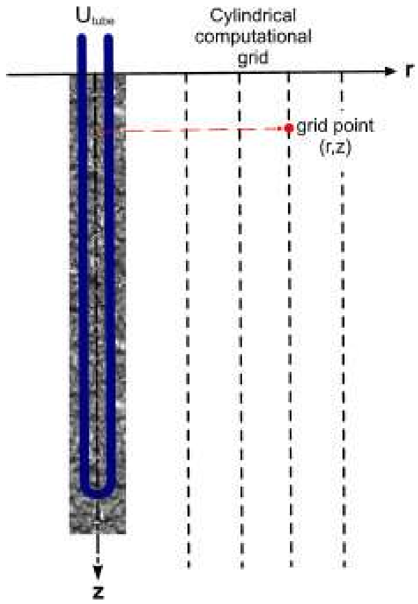


Fig. 7. Borehole grid details.

It is assumed that there is heat transfer between the two BHE sections (input and output/return). The first equation for the BHE input section at its discretized form becomes [11,12]:

$$UA_{g-i}(z) \cdot \left(T(0+\Delta r, z, t) - T_i(z,t) \right) = \dot{m} \cdot C_{p_{medium}} \cdot \left(T_i(z,t) - T_i(z-\Delta z, t) \right) + \quad [1]$$

$UA_{o-i}(z) * (T_o(z,t) - T_i(z,t))$

and for the BHE output/return section:

$$UA_{g-o}(z) \cdot \left(T(0+\Delta r, z, t) - T_o(z,t)\right) = \dot{m} \cdot C_{p_{medium}} \cdot \left(T_o(z,t) - T_o(z+\Delta z, t)\right) - UA_{o-i}(z) * (T_o(z,t) - T_i(z,t)) \quad [2]$$

where $T_o(z,t)$ is temperature of water at point/node at depth z of the output/return section, $T(0+\Delta r,z,t)$ is temperature at the neighbor grid node, $C_{p,medium}$ is water specific heat capacity, $\dot{m}$ is water feed rate in BHE, $1/UA_{g-i}(z)$ is thermal resistance including convection resistance between water and the inner wall of input BHE tube, conduction resistance of tube wall and conduction resistance from the outer tube wall to the neighbor grid node located at $(0+\Delta r,z)$, $1/UA_{g-o}(z)$ is the respective thermal resistance for the output/return section, $1/UA_{o-i}(z)$ is thermal resistance between the two BHE sections (input and output/return). For each time step the two equations 1 and 2 are solved in an iterative manner to achieve the solution stabilization.
The second equation is formulated as:

$$\frac{1}{r} \cdot \frac{\partial \left(k(z) \cdot r \cdot \frac{\partial T}{\partial r}\right)}{\partial r} + \frac{\partial \left(k(z) \cdot \frac{\partial T}{\partial z}\right)}{\partial z} = \rho \cdot C_{p\_ground} \cdot \frac{\partial T}{\partial t} \quad [3]$$

where k(z) is ground thermal conductivity coefficient (depending on the ground depth z), ρ is ground density, C_{p_ground} is ground specific heat capacity, T is temperature and t, is time.

The parameters UA_{g-o}, UA_{g-i} και UA_{o-i} for each depth where ground temperature change (Table III) are calculated using a finite element code. Heat transfer rate between the two sections is calculated by:

$$q_{o\text{-}i} = U_{o\text{-}i} A_{o\text{-}i} (T_o - T_i) \quad [4]$$

where U_{o-i} is overall heat transfer coefficient in W/m^2K, A is surface in m^2, T_i is temperature of BHE input section at a certain depth and T_o is temperature of BHE output/return section at the same depth. For the rest of this paper, $U_{o-i}A_{o-i}$ will be referred as parameter UA_{o-i}. A 2-D grid has been developed (Fig. 8) to simulate BHE and ground section. Ground temperature T_g at a distance r and water temperatures at input and output/return sections T_o and T_i at the same depth are set as boundary conditions.

Data input include heat transfer coefficient h between water and each tube, thermal conductivity, tube thickness and ground thermal conductivity. The code calculates heat transfer rate q_g incoming at the ground cylindrical area of radius r and heat transfer rates q_i and q_o incoming at BHE input and output/return sections at the certain depth (Fig. 9). Following the calculation of q_g, q_i and q_o the following set of equations is solved to find the respective UA:

$$\begin{aligned} q_g &= q_{g\text{-}o} + q_{g\text{-}i} = UA_{g\text{-}o}(T_g - T_o) + UA_{g\text{-}i}(T_g - T_i) \\ q_i &= q_{g\text{-}i} + q_{o\text{-}i} = UA_{g\text{-}i}(T_g - T_i) + UA_{o\text{-}i}(T_o - T_i) \quad [5] \\ UA_{g\text{-}i} &= UA_{g\text{-}o} \end{aligned}$$

where q_{g-o} is heat transfer between ground surface at radius r and BHE output/return section and q_{g-i} is heat transfer between ground surface and BHE input section and q_{o-i} is heat transfer between the two sections. The third equation holds when the material and dimensions of BHE input and output/return sections are the same. UA depends on the soil properties, BHE material and geometry and heat transfer coefficient between water and BHE.

The initial ground temperatures are calculated by curve-fitting the ground temperatures that are measured before BHE operation.

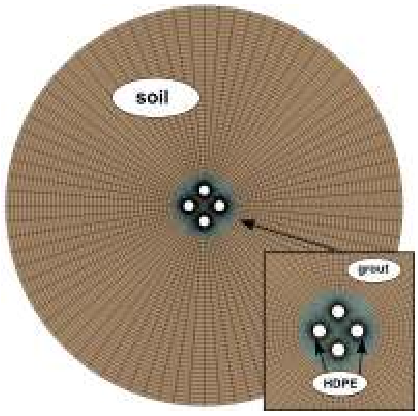


Fig. 8. Borehole 2-D grid details.

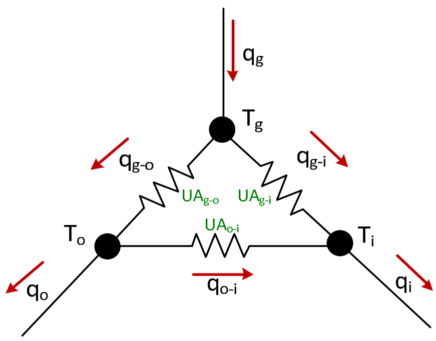


Fig. 9. Heat flows

B. *Typical results and discussion*

In the following typical results from the developed model are presented and discussed. The inlet feed rate was equal to 0.5Kg/s and inlet water temperature was 7^{o}C. It can calculate for how many days of continued operation it can provide the required power and temperature. Fig. 10 shows temperature distribution along the length of BHE after the first day of continuous operation. The blue curve refers to BHE input section, the red curve refers to BHE output/return section and the black curve refers to their average value. The calculated temperature difference between BHE inlet and outlet is about 1.5^{o}C.

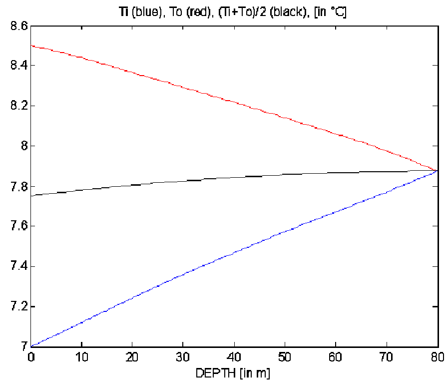


Fig. 10. Temperature distribution along BHE length after 1day of conitnuous operation.

In case BHE operates with interruptions then the respective days that the BHE can provide the desired power and temperature increase. This takes place because during the operation interruption the ground tends to reach the initial temperatures (before BHE operation). In Figs 11 and 12 the system response for 30 days and 6 hours operation per 24h is presented. T_{out}, namely the value of T_o at the BHE outlet reaches 8.5^{o}C at the BHE outlet during the system operation (Fig. 11) while during interruptions the temperature rises to higher values as heat is not absorbed. It is also depicted from Fig. 12 that heat power provided by the BHE decreases during the 30 days period.

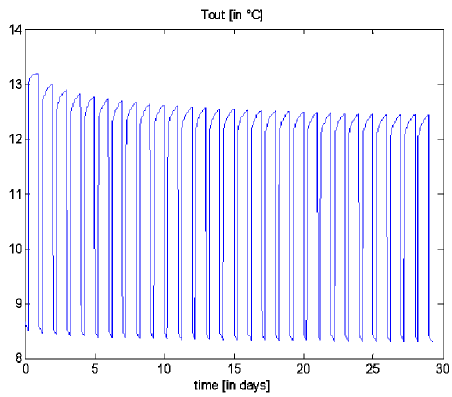


Fig. 11. Temperature at the BHE outlet for 30 days and 6 hours operation per 24h.

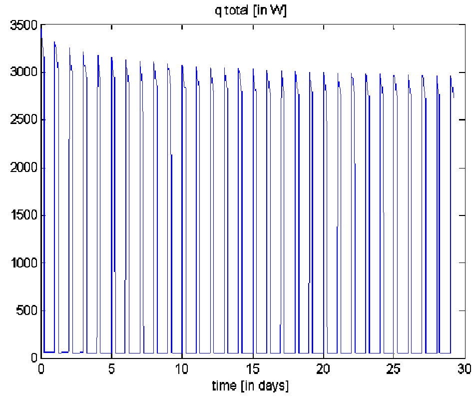


Fig. 12. Thermal power from BHE for 30 days and 6 hours operation per 24h.

Acknowledgment

The work described in this paper was financially supported by the R&D project "Geothermal Heat Pumps of High-End Technology and High Performance - GEOPEAK", COOPERATION 2009 programme, General Secretariat for Research and Technology. Dr. C. Karytsas from CRES has been the Scientific Responsible (Coordinator) of the GEOPEAK project.

References

[1] I. Sarbu, C. Sebarchievici, "General review of ground-source heat pump systems for heating and cooling of buildings", Energy and Buildings vol. 70, pp. 441–454, 2014.

[2] GSHP Market development in Greece Action Plan, CRES, 2012.

[3] GEC policy paper on the European Commission's "Energy Roadmap 2050"

[4] URL: http://www.groundhit.eu

[5] URL: http://www.groundmed.eu

[6] A. Capozza, M. De Carli, and A. Zarrella, "Design of borehole heat exchangers for ground-source heat pumps: A literature review, methodology comparison and analysis on the penalty temperature", Energy and Buildings vol. 55, pp. 369–379, 2012.

[7] Technical Guidance TOTEE 20701-3/2010, Climatic data for Greek areas, TEE, 2012.

[8] H. Yang, P. Cui, Z. Fang, "Vertical-borehole ground-coupled heat pumps: A review of models and systems" Applied Energy vol. 87, Issue 1, pp. 16-27, 2010.

[9] D. Marcotte, P. Pasquier, F. Sheriff, M. Bernier "The importance of axial effects for borehole design of geothermal heat-pump systems" Renewable Energy vol. 35, Issue 4, pp. 763-770, 2010.

[10] T.V. Bandos, Á. Montero, E. Fernández, J.L. G. Santander, J.M. Isidro, J. Pérez, P.J. Fernández de Córdoba, J.F. Urchueguía, "Finite line-source model for borehole heat exchangers: effect of vertical temperature variations" Geothermics vol. 38, Issue 2, pp. 263-270, 2009.

[11] D.A. Anderson, J.C. Tannehill, R.H. Pletcher, "Computational fluid mechanics and heat transfer", Hemisphere Publishing Corporation 1984.

[12] C. Pozrikidis, "Numerical methods in science and mechanics", TZIOLA Eds, 2006.