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Parametric analysis of geothermal residential heating and cooling application

Zoi N. Sagia, Athina B. Stegou, Constantinos D. Rakopoulos

National Technical University of Athens, School of Mechanical Engineering, Department of Thermal Engineering, Heroon Polytechniou 9, 15780, Zografou, Attiki, Greece.

Abstract
A study is carried out to evaluate the efficiency of a Ground Source Heat Pump (GSHP) system with vertical heat exchangers applied to a three-storey terraced building, with total heated area 271.56 m^2, standing on Hellinikon, Athens. The estimation of building loads is made with TRNSYS 16.1 using climatic data calculated by Meteonorm 6.1. The GSHP system is modeled with two other packages GLD 2009 and GLHEPRO 4.0. A comparison of the mean fluid temperature (fluid temperature in the borehole calculated as the average of exiting and entering fluid temperature), computed by above software, shows how close the results are. In addition, a parametric analysis is done to examine the influence of undisturbed ground temperature, ground heat exchanger (GHE) length and borehole separation distance to system's operational characteristics so as to cover building loads. Finally, a 2D transient simulation is performed by means of COMSOL Multiphysics 4.0a. The carrier fluid in the borehole is modeled as a solid with extremely high thermal conductivity, extracting from and injecting to the ground the hourly load profile calculated by TRNSYS. The mean fluid temperature and the borehole wall temperature are computed for an entire year and compared with the values calculated by GLD.

Keywords: Ground source heat pump; Ground heat exchanger; Geothermal; Heating and cooling; Transient analysis.

1. Introduction
Geothermal energy is one more offer from earth to people. Earth is assumed to be a huge heat sink or source for geothermal installations. Many heating and cooling ground plants have been built to cover buildings' needs for air-conditioning.
A typical ground plant or in other words a typical Ground Source Heat Pump (GSHP) system is consisted of a series of closed loops buried in the ground, in which the heat carrier fluid is circulating, coupling with heat pump and distribution circuit to the building. The most common configuration of closed loops, especially when available land is limited, is the vertical one [1]. The pipes are placed in boreholes and grouted with filling material.
The sizing of ground loop is crucial to the whole system sizing and therefore to its effective operation. Various models have been developed to simulate the Ground Heat Exchanger (GHE) response to building loads. Some of them are based on short time-step simulations [2-4] and other on long-term ones [5-7]. In addition, different approaches have been developed by making 1-D [8] and 2-D analysis [9] of GHE operation.

The current study focuses on a fifteen-year simulation of a GSHP system with vertical GHEs which is modeled to cover the energy demands of a three-storey terraced building in Athens. This type of building constitutes a typical Greek residential construction. New, Greek legislation [10] for load calculations is applied.
A combination of different software and dimensional analysis is proposed so as to perform quick and accurate calculations. Software comparison is made, by comparing the calculated outputs.
Emphasis is given on the estimation of the mean fluid temperature of the heat carrier fluid circulating round the GHE. This temperature is calculated as the average of exiting and entering fluid temperature at the GHE. What is more, a parametric analysis is performed to examine the influence of undisturbed ground temperature, GHE length and borehole separation distance to GSHP system characteristics.

2. Building load profile

As it is known, the more precise estimation of building load is, the better sizing of Heating Ventilation Air Conditioning (HVAC) system will be done [11]. The current work attempts to simulate and analyze the operation of a GSHP system for heating and cooling application based on a thorough determination of the building load profile.
A building consisted of three apartments, each one on separate floor, standing on pilotis, is the case study of the present paper. Figure 1 depicts a typical floor layout. The total heated area is 271.56 m^2. The north face of the building, which is facing the road, has 30% of windows while the south 22%. The other two faces attach adjacent buildings. It is situated on Hellinikon, Athens.

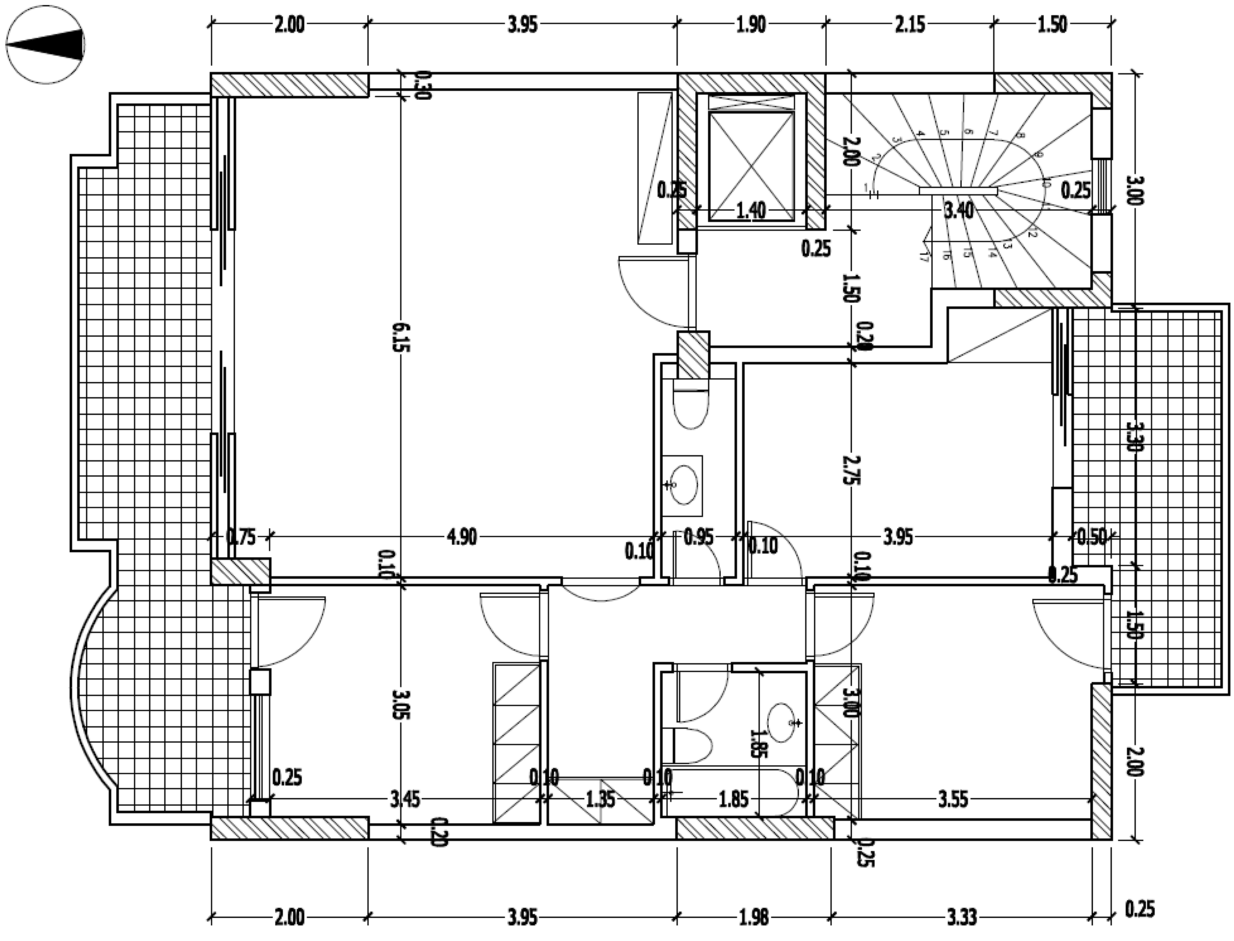


Figure 1. Typical floor layout

A set of climatic data, in form of Typical Meteorological Year (TMY) is calculated by Meteonorm 6.1[12] in order to be used for the building load calculations.
These calculations are performed with TRNSYS 16.1 [13]. The building is divided into 4 thermal zones, one for each apartment and one for the stairwell. All external walls are insulated with slates of

polyurethane which density is ρ=60 kg/m^3, thermal conductivity k=0.023 W/m K and specific heat c_p=1450 J/kg K. In addition, the walls that separate the stairwell from the apartments (internal walls) as well as the floors of different levels are also insulated with slates of fiberglass which density is ρ=100 kg/m^3, thermal conductivity k=0.038 W/m K and specific heat c_p=1030 J/kg K. Insulation slates' thickness is 0.05 m for both external and internal walls. Vertical walls are divided into those with bricks and those with concrete. Table 1 summarizes the main building wall types.

Table 1. Wall type modeling

Wall Type	d_w [m]	m_w [kg/m^2]	U_w [W/m^{2}K]
First floor	0.250	427.88	0.401
Second and third floor	0.217	423.46	1.195
Flat roof	0.380	496.18	0.390
External concrete wall	0.385	752.38	0.396
External brick wall	0.365	538.38	0.348
Internal concrete wall	0.381	749.98	0.599
Internal brick wall	0.351	363.98	0.634

All external walls have solar absorptance 0.40 apart from the flat roof which absorptance is 0.65 and all internal 0.0. The convective heat transfer coefficient of external vertical wall with indoor air is 7.7 W/m^2 K and with outdoor 25 W/m^2 K whereas, the convective heat transfer coefficient of internal vertical wall with air is 7.7 W/m^2 K. The same coefficient for the external horizontal wall of the first floor is 5.88 W/m^2 K with indoor air and 25 W/m^2 K with outdoor whereas, for the internal horizontal walls of the second and third floor is 5.88 W/m^2 K. Flat roof's convective heat transfer coefficient with indoor air is 10 W/m^2 K and with outdoor 25 W/m^2 K. It is worth saying that the above values derive from new, Greek legislation for buildings [10], applied on January 2011 and, on this legislation is also based the wall modeling [14, 15] and thus the calculated thermal transmittance values (see Table 1). The building bears double insulating glazing with thermal transmittance U=2.83 W/m^2 K and solar heat gain coefficient g=0.755. Windows' frame is 20% of the window area, with U=3.5 W/m^2 K. Shading coefficients are also calculated for different wall and glazing orientation based on new, Greek legislation on buildings. The heating schedule [14] sets the indoor air temperature at 293.15 K (20^{o}C) with 40% relative humidity for 18 hours and the cooling one [14] sets the indoor air temperature at 299.15 K (26^{o}C) with 45% relative humidity. Ventilation [14] is counted for 0.25 air-change/hour and infiltration [14] for 0.26 regarding:

$$V_{\inf} = \sum (l \cdot a_{\inf}) \cdot R_{\inf} \cdot H_{\inf} \tag{1}$$

adding the air exchange from fireplaces and chimneys, where $V_{\inf}$ is the infiltration volume (m^3/h), l the perimeter of all building's openings (m), $a_{\inf}$ the rate of penetration of air exposure (m^3/(h m)), $R_{\inf}$ the rate of penetration due to opening's geometrical attributes and $H_{\inf}$ the factor of opening's position and air force exposure.

Annual heating demand of the building is 33.78 kWh/m^2 whereas cooling demand is 27.34 kWh/m^2.

3. GSHP system simulation

3.1 GLD and GLHEPRO simulation

The GSHP system is modeled through widely known software GLD 2009 [16] and GLHEPRO 4.0 [17]. These simulations are based on the energy demands that have been calculated by TRNSYS model. The Peak Load Analysis Tool [18] reads the annual TRNSYS heating and cooling load profile so as to determine the values of the peak heating and cooling loads for each month of the year (see Table 2) and their durations. Moreover, in Table 2 climatic data are presented in an attempt to clarify the climatic area for which the loads have been calculated. However, it is difficult to claim for generalizations. Considering the same climatic data and making load calculations for areas where are in the south suburbs of Athens (not far away from Hellinikon) but they are much more urbanized would lead to a significant underestimation of cooling load.

It is important to highlight that two durations are determined one for the peak heating load and one for the cooling one, constants for the whole year. The peak load values and peak load duration are these that result at a peak normalized temperature response [18] of GHE closest to one. This normalized temperature is the ratio between the calculated temperature difference of the water entering – exiting the GHE and the maximum temperature difference appears at the GHE considering the full hourly load profile. Figures 2 and 3 show the temperature response of GHE for the GSHP system heating and cooling design day, which has been calculated to be the 16^{th} and 231^{st} day of the year respectively, applying the "maximum over duration" method. This method applies the maximum load of the design day for each hour of the peak duration. Judging from Figures 2, 3, 2-hour duration is selected for the heating season and 8-hour duration for the cooling one.

Table 2. Ground source heat pump system loads and climatic data

Month	Total Loads [kWh]		Peak Loads [kW]		Climatic Data [14]		
	Heating	Cooling	Heating	Cooling	T_a [°C]	G_h [W/m^2]	D_h [W/m^2]
JAN	2415.963	0.000	11.271	0.000	10.00	89	38
FEB	2257.352	0.000	10.888	0.000	10.20	111	62
MAR	1768.731	0.000	9.724	0.000	11.90	140	82
APR	572.876	0.000	6.133	0.000	15.20	203	100
MAY	0.000	27.273	0.000	1.138	20.70	244	118
JUN	0.000	1260.391	0.000	5.559	25.70	278	112
JUL	0.000	2655.869	0.000	6.893	28.40	286	109
AUG	0.000	2614.896	0.000	7.187	28.20	269	91
SEP	0.000	823.885	0.000	4.643	23.80	216	81
OCT	0.000	41.910	0.000	1.261	19.50	143	68
NOV	332.533	0.000	6.144	0.000	15.40	92	49
DEC	1825.350	0.000	10.372	0.000	11.60	71	37

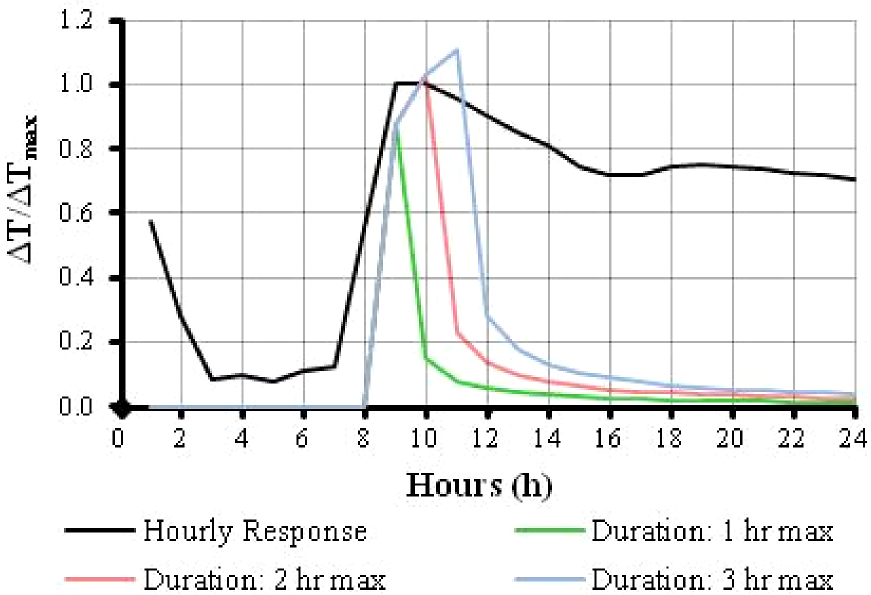


Figure 2. Heating design day temperature response

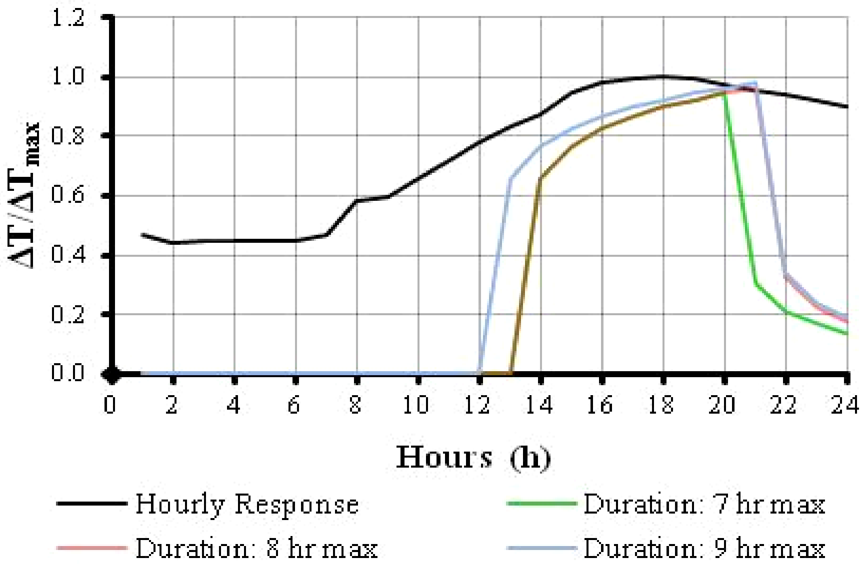


Figure 3. Cooling design day temperature response

The basic scenario of the GSHP system is consisted of 3 boreholes with one single U-tube GHE having average radial pipe placement at each one. The ground properties [17] are assumed to be the ones of a typical average rock ground.

The undisturbed ground temperature [12, 17] is approximately regarded as the average annual air temperature, making a roughly but still satisfactory estimation of its value. As this calculation results in a high temperature value of 291.45 K (18.3°C), the circulating fluid through the GHE is conceived to be pure water. A 6740 Reynolds value ensures turbulent flow through U-tube pipes.

The heat pump [19] is dimensioned at 60% of the peak heating load, which leads to a satisfactory coverage (approximately 90%) of the total heat energy required by the building over the heating period, avoiding repeatedly interruptions of its operation. The minimum fluid temperature [20] of the ground loop entering the heat pump is not supposed to be less than 283.45 K (10.3°C) and the maximum fluid temperature not to be more than 303.45 K (30.3°C). The main GSHP system parameters are presented in Table 3.

Table 3. Main Ground Source Heat Pump system parameters

Parameter	Value
Borehole number	3
Borehole length	70 m
Borehole separation	4.5 m
Borehole diameter	0.11 m
Borehole thermal resistance	0.1292 m K/W
Volumetric flow rate/ Borehole	0.00015 m^3/s
U-tube inside diameter	0.0218 m
U-tube outside diameter	0.0267 m
Ground thermal conductivity	2.420 W/m K
Ground volumetric heat capacity	2343000 J/m^3 K
Ground density	2803 kg/m^3
Undisturbed ground temperature	291.45 K
Grout thermal conductivity	1.5 W/m K
Grout volumetric heat capacity	1600000 J/m^3 K
Grout density	1000 kg/m^3
Pipe thermal conductivity	0.4 W/m K
Pipe volumetric heat capacity	2162000 J/ m^3 K
Pipe density	940 kg/m^3

3.2 COMSOL simulation

Simulating GHE operation by means of finite element analysis is an increasingly common practice [21]. A 2D transient simulation is done by the Heat Transfer Module of COMSOL Multiphysics 4.0a [22, 23]. The geometric and physical properties of the model are those of the basic scenario (see Table 3 for subdomains' characteristics).

The heat carrier fluid in the GHE is modeled as a solid with density ρ=999.6 kg/m^3, extremely high thermal conductivity k=1000 W/m K and specific heat c_p=4192 J/kg K. The governing equation [24] is:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla(-k\nabla T) = Q + q_s T \tag{2}$$

where ρ is the density (kg/m^3), c_p the specific heat capacity (J/kg K), T the temperature (K), t the time (s), k the thermal conductivity (W/m K), Q the heat source that is set to be equal to the hourly load profile calculated by TRNSYS for an entire year (W/m^3) and q_s the production or absorption coefficient (W/(m^3 K)).

The infinite ground is simulated by a circle with 50 m radius which is by far bigger than boreholes' radius. Its circumference is set to be at the undisturbed ground temperature.

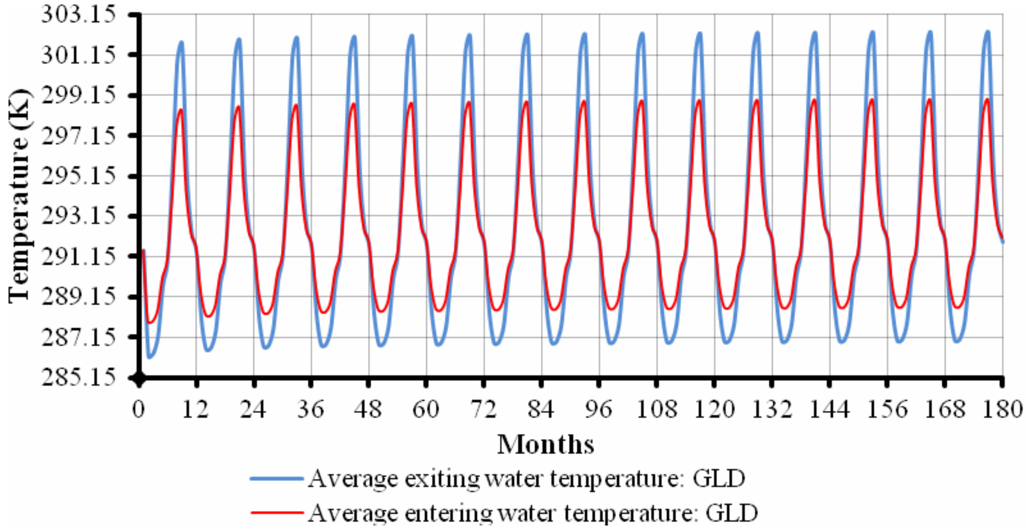
4. Parametric analysis and results

Sizing GSHP system by GLD and GLHEPRO software for the given building loads and operation range of the first loop of the heat pump, the boreholes' optimum length is calculated 70 m. For this basic scenario, the average water temperatures exiting and entering the heat pump are presented in Figure 4 for a fifteen-year period. Table 4 shows how close the calculated values by the two above software are. The fourth and the fifth column of Table 4 is calculated as the difference between the two maximum and minimum software values respectively, divided by the temperature of first column for calculating ΔT_{max} percentage and of second column for calculating ΔT_{min} percentage. What is more, judging from Figure 4a three-degree difference is achieved between the average exiting and entering water temperature, which ensures the satisfactory operation of the ground loop.

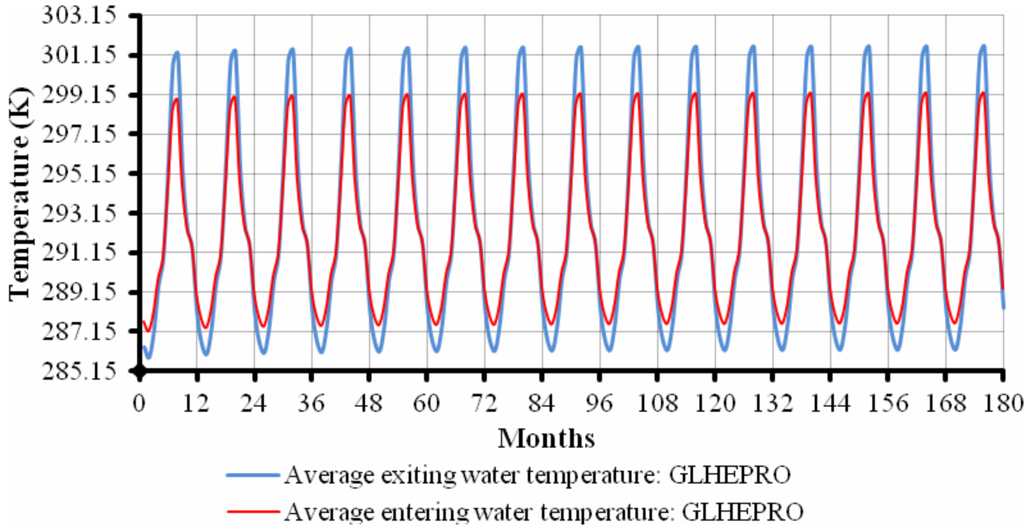
Figure 5 depicts the mean fluid temperature evolution for the basic scenario calculated by GLD and GLHEPRO. Once again, the two estimations of the mean temperature of the circulating fluid round the boreholes are very close, despite the fact that GLD calculation starts from 291.15 K which equals to undisturbed ground temperature and is approximately 4.5 degrees higher than GLHEPRO initial temperature.

Table 4. Circulating fluid temperature through the GHE loop for the basic scenario

Water Temperature	T_{max} [K]	T_{min} [K]	ΔT	ΔT_{max} [%]	ΔT_{min} [%]
Average exiting water temperature by GLD	302.25	286.16	16.09	0.218	0.115
Average entering water temperature by GLD	298.93	287.90	11.03	-0.100	0.257
Average exiting water temperature by GLHEPRO	301.59	285.83	15.76	-0.219	-0.115
Average entering water temperature by GLHEPRO	299.23	287.16	12.07	0.100	-0.258
Mean fluid temperature by GLD	300.59	287.03	13.56	0.060	0.188
Mean fluid temperature by GLHEPRO	300.41	286.49	13.92	-0.060	-0.188



(a)



(b)

Figure 4. Average exiting and entering water temperature evolution for the basic scenario calculated by: (a) GLD; (b) GLHEPRO

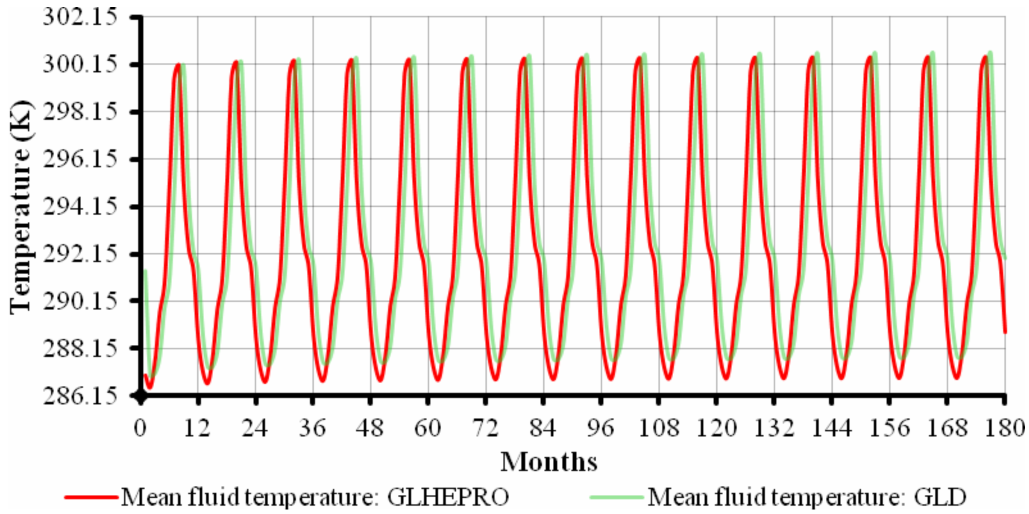


Figure 5. Mean fluid temperature evolution for the basic scenario

It is worth saying that GLHEPRO 4.0 [17] implements Eskilson's method [5] for the design of vertical GSHP system. GLD 2009 [16] also implements Eskilson's method within the Borehole Design module in conjunction with the Average Block Loads module and this is the option used in the present work and not the Zone Manager module which is based on cylindrical source model.
Eskilson method [5] conceives the borehole as a finite line sink in a homogenous medium, the ground. It depends on the dimensionless g-function, which indicates the temperature response of a fixed borehole configuration to a step change in heat extraction or rejection rate. The g-function is given by:

$$T_b - T_0 = \frac{q_0'}{2 \cdot \pi \cdot k} g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) \tag{3}$$

where T_b is the average temperature at borehole radius (°C), T_0 the undisturbed ground temperature (°C), q_0' the heat flux per unit length (W/m), k the ground thermal conductivity (W/m K), t the time (s), $t_s = \frac{H^2}{9 \cdot a}$ the steady state time scale, r_b the borehole radius (m), H the active borehole length (m), a the thermal diffusivity of the ground (m^2/s).
For the optimum borehole length of 70 m, calculated for the basic scenario, GLHEPRO also gives as an output the g-function. Varying the centre-to-centre borehole separation distance from 3.5 m to 6.5 m with one meter step, g-function values change accordingly. Figure 6 shows that for the three studied boreholes, thermal interference appears among them after:

$$\log\left(\frac{t}{t_s}\right) = -5 \Rightarrow t = \frac{t_s}{150} \tag{4}$$

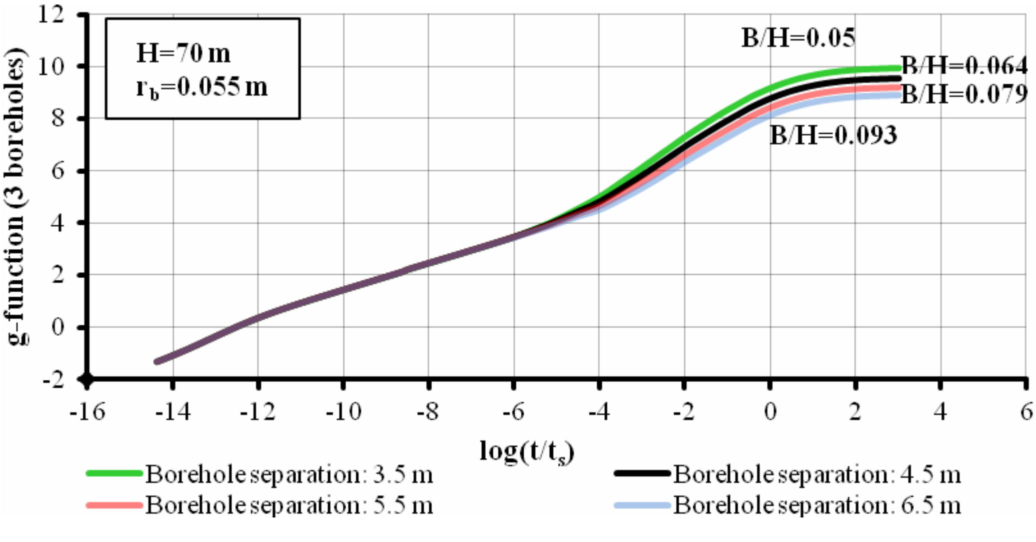


Figure 6. g-function for 70 m borehole length calculated by GLHEPRO software

Figure 7 depicts g-functions for different borehole lengths with 4.5 m fixed borehole separation distance. These lengths have been derived from borehole sizing of different scenarios, which have small modifications from the basic one. Table 5 shows theses scenarios which are examined in the current study as part of parametric analysis.
Sizing software calculates borehole length considering the heating and cooling demands. In the current study the values of these demands are very close which accounts for a viable working system as the ground's heat depletion during winter time will be almost replenished during summer time. However, the little higher value of peak heating load comparing to cooling one leads to heating dominated system sizing. As a result, in case of smaller undisturbed ground temperature borehole length will increase so as the heat supply to GSHP system through the ground to be accordingly increased and cover the given heating demand (see Table 5 comparing Basic Scenario with Scenario IV, V, VI).

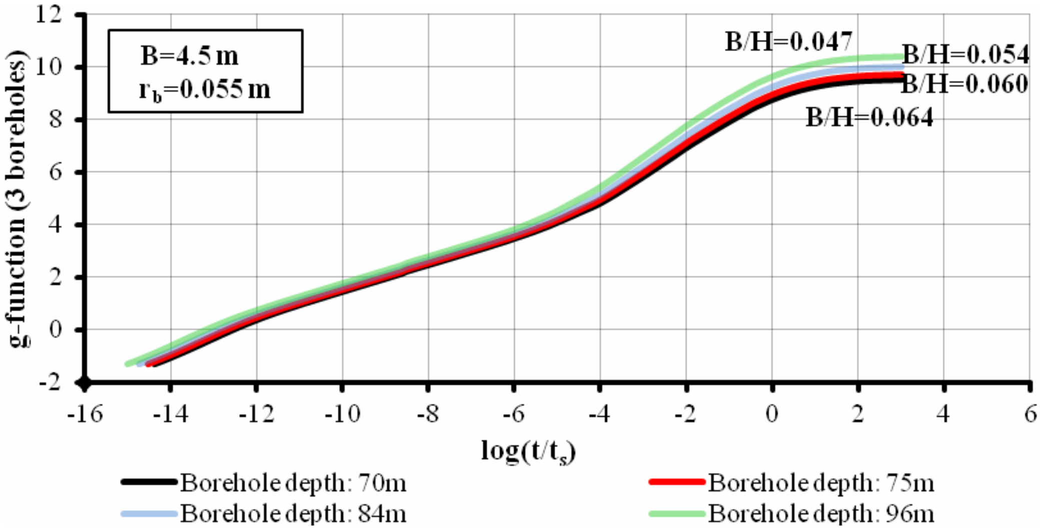


Figure 7. g-function for 4.5 m centre-to-centre borehole separation distance calculated by GLHEPRO software

Table 5. Modifications of the basic scenario

Scenario	T_g [K]	B [m]	H [m]
Basic Scenario	291.45	4.5	70
Scenario I	291.45	3.5	70
Scenario II	291.45	5.5	70
Scenario III	291.45	6.5	70
Scenario IV	290.45	4.5	75
Scenario V	289.45	4.5	84
Scenario VI	288.45	4.5	96

Modifying the basic scenario, just by reducing undisturbed ground temperature from 291.45 K (18.3°C) to 288.45 K (15.3°C) with one degree step, leads to a relevant reduction of mean circulating fluid temperature and thus to borehole wall temperature (see Figures 8, 9). Studying the minimum temperatures evolution of each scenario, it is obvious a small increase over the first six-year period until the GSHP system begins to tend towards its steady-state situation.

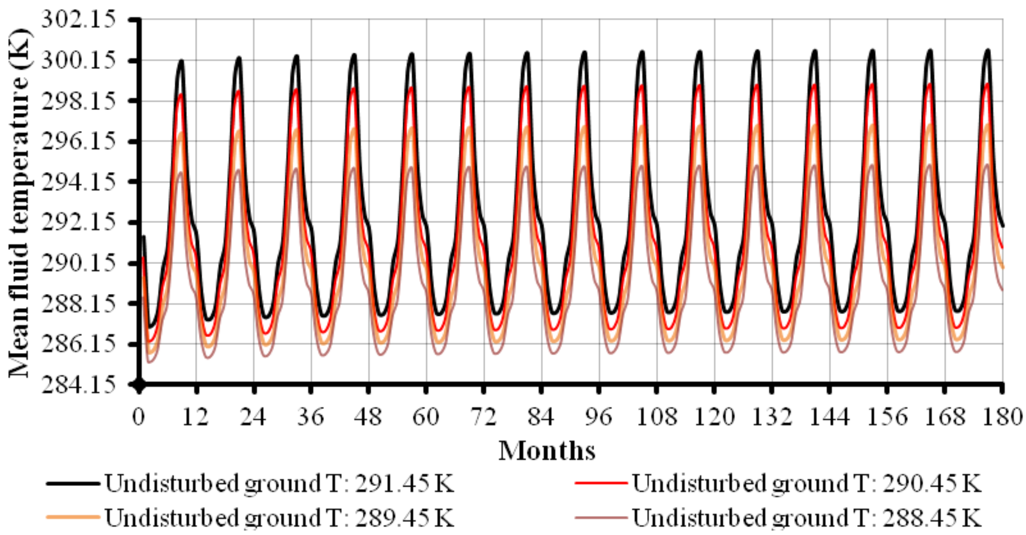


Figure 8. Mean fluid temperature evolution calculated by GLD software

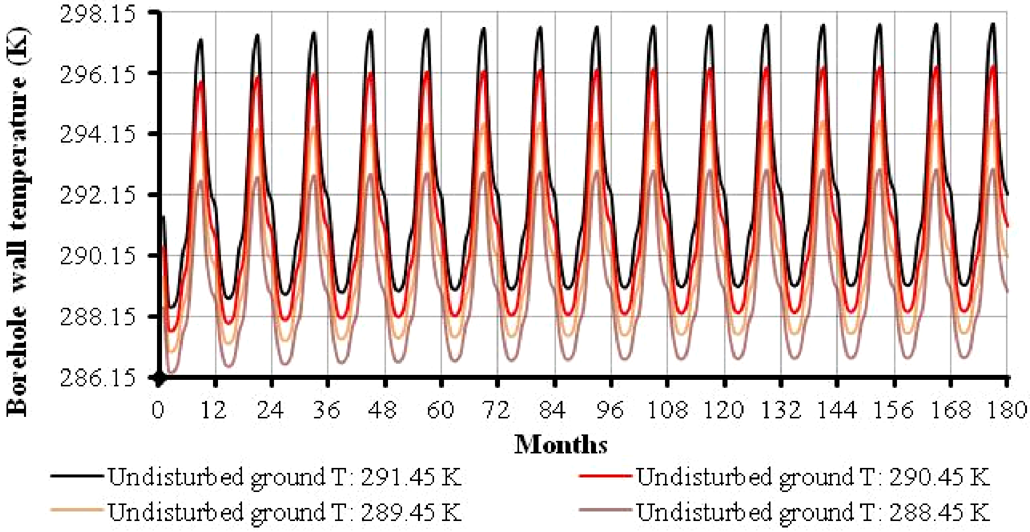


Figure 9. Borehole wall temperature evolution calculated by GLD software

Table 6 shows a numerical comparison between the maximum and minimum temperatures of the studied scenarios, which appear at cooling and heating season respectively. Results indicate that 1 K reduction in undisturbed ground temperature leads to an average 1.9 K reduction in maximum mean water temperature circulating round the ground loop and in an average 0.6 K reduction in minimum one. Correspondingly, 1 K decrease to undisturbed ground temperature results in an average drop of 1.6 K to maximum borehole wall temperature and in an average drop of 0.7 K to minimum one. It is also important to highlight that maximum borehole wall temperature has a general drop of around 2.5 K to maximum mean water temperature.

Table 6. Numerical comparison of scenarios outputs

Scenario	$T_{m,max}$ [K]	$T_{m,min}$ [K]	ΔT_m	$T_{b,max}$ [K]	$T_{b,min}$ [K]	ΔT_b
Basic Scenario	300.59	287.03	13.56	297.74	288.50	9.24
Scenario IV	298.95	286.34	12.61	296.31	287.71	8.60
Scenario V	296.89	285.80	11.09	294.55	287.01	7.54
Scenario VI	294.96	285.27	9.69	292.93	286.32	6.61

Attempting to investigate the evolution of mean fluid temperature through the ground loop and borehole wall temperature over one-year time, another method is followed which ignores the presence of heat pump and assumes that building load profile would be covered solely by GHEs. COMSOL and GLD predict these temperature evolutions, which are depicted in Figures 10, 11, by calculating certain values. Trying to correlate these values with polynomial equations the following relations are defined.
For the mean fluid temperature, COMSOL correlation is defined by:

$$y = -0.00004x^6 + 0.0027x^5 - 0.0469x^4 + 0.2088x^3 + 1.0953x^2 - 7.4676x + 293.53 \tag{5}$$

where y is the temperature (K), x the month and $R^2 = 0.9851$ the correlation coefficient.
Respectively, GLD correlation, regarding 100 m borehole length is:

$$y = 0.0007x^6 - 0.026x^5 + 0.3779x^4 - 2.785x^3 + 11.305x^2 - 23.313x + 305.86 \tag{6}$$

with $R^2 = 0.9786$,
whereas GLD correlation for the basic scenario is:

$$y = 0.0013x^6 - 0.0479x^5 + 0.6678x^4 - 4.599x^3 + 16.936x^2 - 31.505x + 309.96 \tag{7}$$

with $R^2 = 0.9692$.
For the borehole wall temperature, COMSOL correlation is given by:

$$y = 0.000002x^6 + 0.0004x^5 - 0.0136x^4 + 0.1431x^3 - 0.448x^2 - 0.2901x + 291.75 \tag{8}$$

with correlation coefficient $R^2 = 0.9974$.
GLD correlation for the same temperature, regarding 140 m borehole length is:

$$y = 0.0003x^6 - 0.0125x^5 + 0.181x^4 - 1.3282x^3 + 5.355x^2 - 11.005x + 298.25 \tag{9}$$

with $R^2 = 0.9792$,
whereas GLD correlation for the basic scenario is:

$$y = 0.0009x^6 - 0.032x^5 + 0.4461x^4 - 3.0659x^3 + 11.244x^2 - 20.868x + 303.7 \tag{10}$$

with $R^2 = 0.9713$.

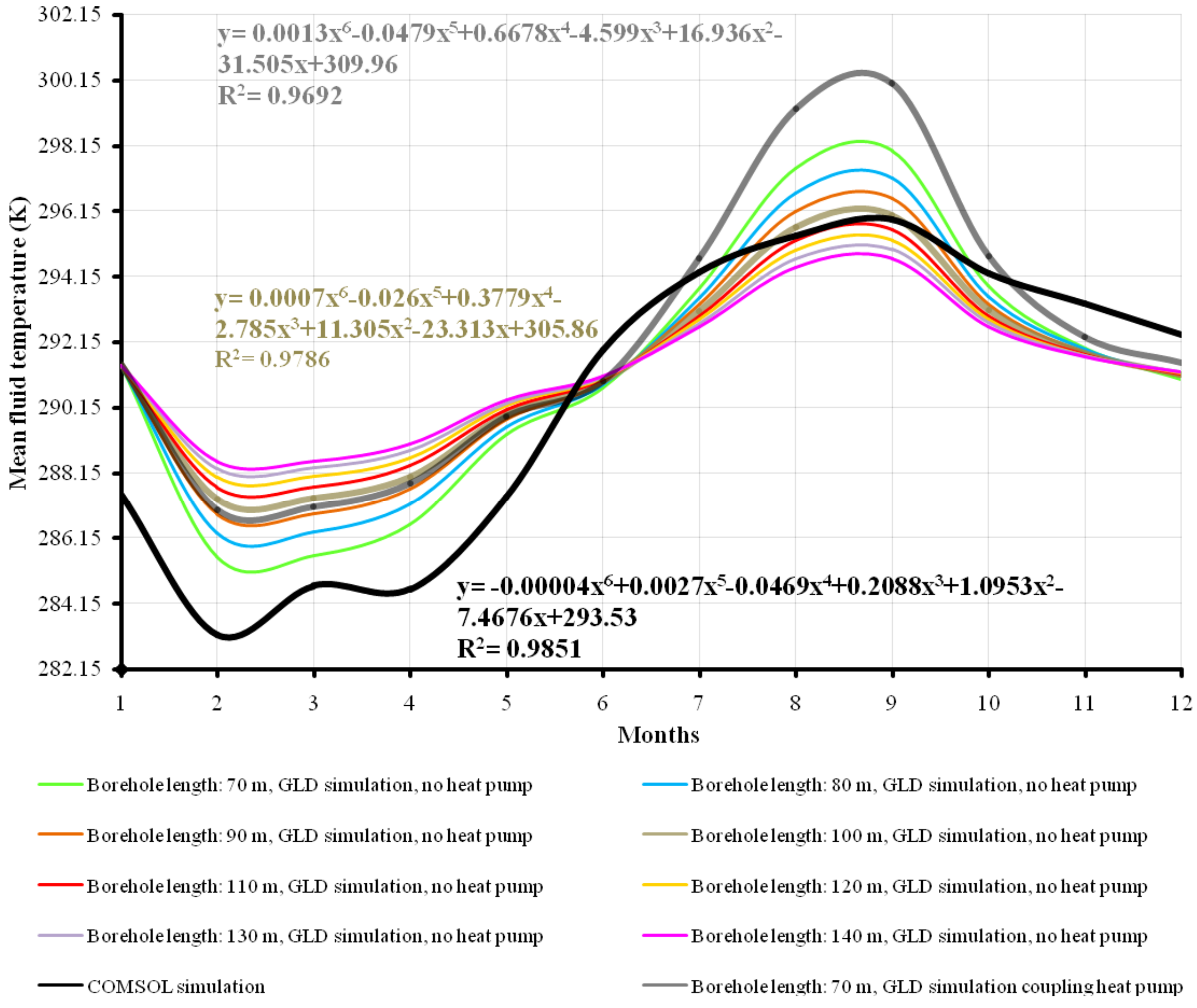


Figure 10. Mean fluid temperature evolution for 4.5 m borehole separation distance and 291.45 K undisturbed ground temperature

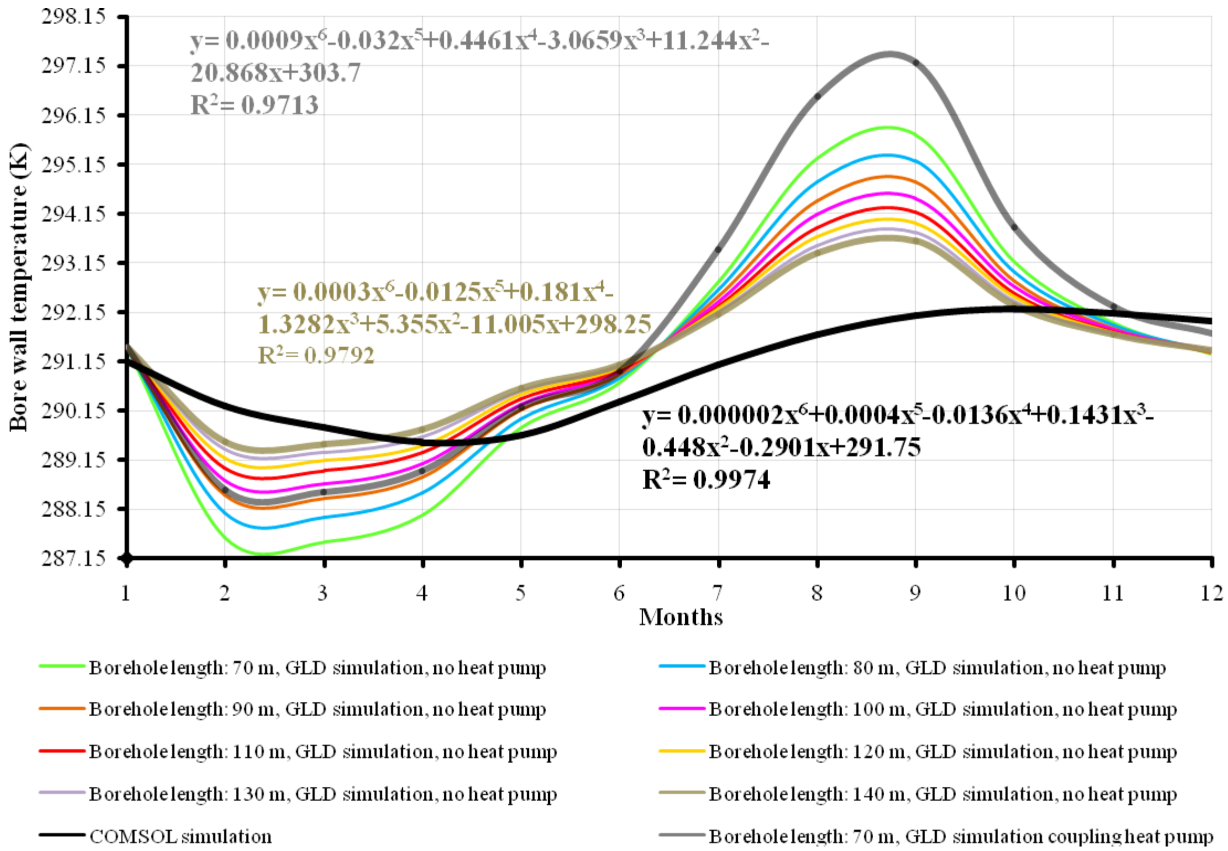


Figure 11. Borehole wall temperature evolution for 4.5 m borehole separation distance and 291.45 K undisturbed ground temperature

Judging from Eqs. (5) and (6) the mean fluid temperature estimations are very close for the cooling season, with maximum difference less than 1 K, whereas are far enough for the heating one, with maximum difference approximately 4 K. The reason for the deviation is that GLD performs a series of internal calculations (solving equations) referring to line source model [16] whereas COMSOL solves heat transfer equation in the defined subdomains by means of finite element method [22]. Comparing GLD simulations with no heat pump, in Figure 10, the one with 70 m borehole length is much closer to COMSOL simulation for the heating season than that with 100 m borehole length. Judging from Eqs. (8) and (9) the borehole wall temperature evaluations are closer for the heating season than for the cooling one, contrary to the mean fluid temperature expressions. This remark highlights the difficulty of simulating heat transfer process using different types of analysis. What is more, GLD simulation with 140 m borehole length is closer to COMSOL one than that of 100 m length for the heating season (see Figure 11).

Despite the fact that COMSOL approach is not based on reading calibrated loads, an intentional selection so as to simulate real load profile, the temperature distribution trend through the year is acceptable and enables user to visualize it around borehole field through software's interface. Eqs. (5) and (8) are applicable to rough temperature estimations (average deviation ±2.5 K) when annual heating and cooling demand values are close and approximately equal to 30 kWh/m^2 and it is assumed heat pump absence.

5. Conclusion

All in all, in the present work an extensive sizing study of a GSHP system in Hellinikon, is pursued to determine the influence of several factors to the distribution of mean temperature of the fluid circulating round the ground loop and the borehole wall. Smaller undisturbed ground temperatures lead to smaller mean fluid temperatures and even smaller borehole wall ones. By increasing the separation distance between the boreholes, thermal interference decreases among them. A decrease at undisturbed ground temperature results in an increase at GHE length so as a certain heating load to be covered. GLD and GLHEPRO simulations lead to quite similar results while COMSOL simulation attempts to implement a different mathematical approach assuming the operation of ground heat exchangers without heat pump. All three software can be used in GSHP system modeling but, the best choice depends on the desired degree of detail in the study. GLD and GLHEPRO software are proposed for GSHP system sizing whereas COMSOL approach is much more theoretical.

Nomenclature

B borehole separation, m
c_p specific heat, J/(kg K)
d thickness, m
D Mean irradiance of diffuse radiation, W/m^2
G Mean irradiance of global radiation, W/m^2
H active borehole length, m
H_{inf} factor of opening's position and air force exposure
k thermal conductivity, W/(m K)
m mass per unit area, kg/m^2
l perimeter of all building's openings, m
Q heat source, W/m^3
q_0' heat flux per unit length, W/m
q_s production or absorption coefficient, W/(m^3 K)
r radius, m
R^2 correlation coefficient
R_{inf} rate of penetration due to opening's geometrical attributes
t time
T, y temperature, K
t_s steady state time scale
U thermal transmittance, W/(m^2 K)
x month

Greek symbols

a ground thermal diffusivity, m^2/s
a_{inf} rate of penetration of air exposure, m^3/(h m)
ρ density, kg/m^3

Subscripts and superscripts

a Ambient
b Borehole
g Ground
h Horizontal
m Mean
w Wall

References

[1] Self S.J., Reddy B.V., Rosen M.A. Geothermal Heat Pump Systems: Status Review and Comparison with Other Heating Options. Proceedings of the 3rd International Conference on Applied Energy. Perugia, Italy, 2011.

[2] Hellström G. Ground Heat Storage Thermal Analysis of Duct Storage Systems. Theory, Part I, University of Lund, Department of Mathematical Physics, 1991.

[3] Yavuzturg C., Spitler J.D. Comparative study to investigate operating and control strategies for Hybrid Ground Source Heat Pump Systems using a short time-step simulation model. ASHRAE Transactions 2000, 106(2), 192-209.

[4] Partenay V., Riederer P., Salque T., Wurtz E. The influence of the borehole short-time response on ground source heat pump system efficiency. Energy and Buildings 2011, 43, 1280-1287.

[5] Eskilson P. Thermal analysis of heat extraction boreholes. Doctoral thesis, University of Lund, Department of Mathematical Physics, 1987.

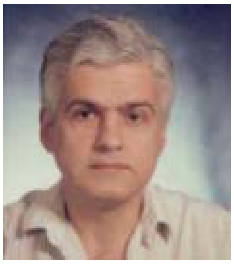
[6] Signorelli S., Kohl T., Rybach L. Sustainability of production from borehole heat exchanger fields. Proceedings of the World Geothermal Congress. Antalya, Turkey, 2005.

[7] Fossa M. The temperature penalty approach to the design of borehole heat exchangers for heat pump applications. Energy and Buildings 2011, 43, 1473-1479.

[8] Zeng H., Diao N., Fang Z. A finite line-source model for boreholes in geothermal heat exchangers. Heat Transfer: Asian Research 2002, 31, 558-567.
[9] Yavuzturk C., Spitler J.D., Rees S.J. A transient two-dimensional finite volume model for the simulation of vertical U-tube ground heat exchangers. ASHRAE Transactions 1999, 105, 465–474.
[10] Greek Presidential Degree 100. Energy Building Inspectors, Boiler and heating and air conditioning. Greek Government 177/A/6-10-2010, 2010.
[11] Dascalaki E.G., Droutsa K., Gaglia A.G., Kontoyiannidis S., Balaras C.A. Data collection and analysis of the building stock and its energy performance-An example for Hellenic buildings. Energy and Buildings 2010, 42, 1231-1237.
[12] Meteonorm Software, v.6.1, 2010.
[13] TRNSYS Software, v.16.1, 2007.
[14] Technical Chamber of Greece. Comprehensive national standards parameters for calculating the energy performance of buildings and issuing of energy performance certificate. Technical Instruction 20701-1/2010, Building PECA Minister Decision 17178/2010, Official Gazette 1387/B/9-2-2010.
[15] Technical Chamber of Greece. Thermophysical properties of construction materials and control of thermal insulation efficiency of buildings. Technical Instruction 20701-2/2010, Building PECA Minister Decision 17178/2010, Official Gazette 1387/B/9-2-2010.
[16] GLD Software 2009, Gaia Geothermal.
[17] GLHEPRO, v.4.0, 2007.
[18] J.R. Cullin. Peak Load Analysis Tool, 2007.
[19] Rosén B., Gabrielsson A., Fallsvik J., Hellström G., Nilsson G. Systems for ground source heating and cooling -a status report- in Swedish, Varia 511, Statens Geotekniska Institut Linköping, 2001.
[20] VDI. Thermal use of the underground: Ground source heat pump systems. Richtlinien VDI 4640, Blatt 2/Part 2. Verein Deutscher Ingenieure, Düsseldorf, Germany, 2001.
[21] Khalajzadeh V., Heidarinejad G., Srebric J. Parameters optimization of a vertical ground heat exchanger based on response surface methodology. Energy and Buildings 2011, 43, 1288-1294.
[22] COMSOL Multiphysics, v.4.0a. Heat Transfer Module, 2010.
[23] Lamarche L., Kajl S., Beauchamp B. A review of methods to evaluate borehole thermal resistances in geothermal heat-pump systems. Geothermics 2010, 39(2), 187-200.
[24] Mills A.F. Basic heat and mass transfer. Richard D. Irwin Inc, 1995.

Zoi N. Sagia Mechanical Engineer, National Technical University of Athens, Greece 2006, Master of Science in Environment and Development, National Technical University of Athens, Greece 2009. Major field of study: Heat Transfer, Energy saving applications in buildings, Geothermal Energy. Recent publication: Zoi Sagia, C. Rakopoulos, E. Kakaras. Cooling dominated Hybrid Ground Source Heat Pump System application. Applied Energy 94 (2012) 41-47.
E-mail address: zoisagia@mail.ntua.gr

Athina B. Stegou
Professor Dr. Mechanical Engineer
Section of Thermal Engineering
School of Mechanical Engineering
National Technical University of Athens
See Personal Homepage: http://courseware.mech.ntua.gr/ml22139/.
E-mail address: asagia@central.ntua.gr



Constantinos D. Rakopoulos
Professor Dr. Mechanical Engineer
Section of Thermal Engineering
School of Mechanical Engineering
National Technical University of Athens
See Personal Homepage: http://users.ntua.gr/cdrakops.
E-mail address: cdrakops@central.ntua.gr

