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Integration of Ground Source Heat Pump System and Gas Turbine for Heating Purpose of GT Surrounding Buildings

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ABSTRACT

Ground source heat pump (GSHP) systems are becoming widespread due to their high energy efficiency both in heating and cooling mode. In this study I try to integrate GSHP and gas turbine (GT). The energy of GT exhaust gases can be used as an initial power of GSHP systems specially during cold seasons. In this paper methods are given to store the energy of GT exhausted gases in ground during the warm seasons and reuse it in cold seasons for heating purpose of the building. In order to store this energy in ground, spiral GHEs are used and analyzed. After storing partial energy of GT exhaust gases in ground in summer, it can be reused during cold seasons for heating purpose of surrounding buildings through GSHP systems or directly. Furthermore, in this study, thermal behavior of nine spiral GHEs is investigated computationally and experimentally in heating mode of GSHP system. Storage processes of GT exhausted gases energy are simulated by COMSOL environment and the effects of the energy storage process on thermal performance of nine spiral GHEs are analyzed computationally. Since gases are exited GT in high temperature, the temperature of ground around spiral GHEs during storage process is highly increased. Simulation results of GSHP systems in this study show that the performance of GSHP is well increased. The methods that are given in this paper can reduce the energy cost of buildings and are also increase the thermal performance of GSHP systems.

1. INTRODUCTION

Nowadays gas turbines (GTs) are becoming popular based on their attractive features such as low capital cost, compact size, high flexibility, fast starting and loading and etc. In last decades, small size (or large) GT power plants are mostly built near building residences to supply their electricity demand. This issue let them to produce their own electricity themselves. In comparison with other electricity production methods, the efficiency of GT is low. Environmental conditions are highly affected the efficiency of GT. In GTs, thermal energy of exhaust gases is wasted in environment. This energy can be used for different purposes. First, it can be used for regeneration. Since the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the temperature, the high pressure air leaving the compressor can be heated by exhaust gasses in counter flow heat exchanger which is known as regenerator. Regeneration is leaded to increase in thermal efficiency of GT. Second, this energy can be used in a heat exchanger of generator of absorption refrigeration cycle to increase the thermal efficiency of GT (El-Shazly et al.(2016), Mohapatra et al. (2015) and Tucakovic et al.(2013)). Third, during hot season (climate) turbine exhaust gases energy can be stored in ground and then reused during cold climate specially for heating purposes. Since gases are exhausted turbine in high temperature, the high amount of heat can be stored in ground. Heat can be stored in ground by using several ground heat exchangers (GHEs) with specific distance between them. Stored energy in ground can be reused and extracted through ground source heat pump (GSHP) system.

Reduction of the building energy demand and greenhouse gases emissions are significant topics especially in European policies of future planning. These policies tolerate the spreading of renewable energy sources for space heating and cooling. Geothermal energy is known as one the most efficient renewable energies in the world. It is clean and sustainable. Since stored energy in ground is used through GSHP systems, importance of using them is increased. GSHP system contains two main part, heat pump and GHE. Each part has high portion in performance of GSHP system and needs to be designed exactly. Here I only analyze spiral GHEs which are popular among shallow ones (Bortoloni et al.(2017), Atam and Helsen(2016)). Results of Dehghan et al.(2016) work show that, between different configurations, formation of nine spiral GHEs (N=9) with six meter distance between them (d=6m) can be suitable for the most individual independent houses (Villas).

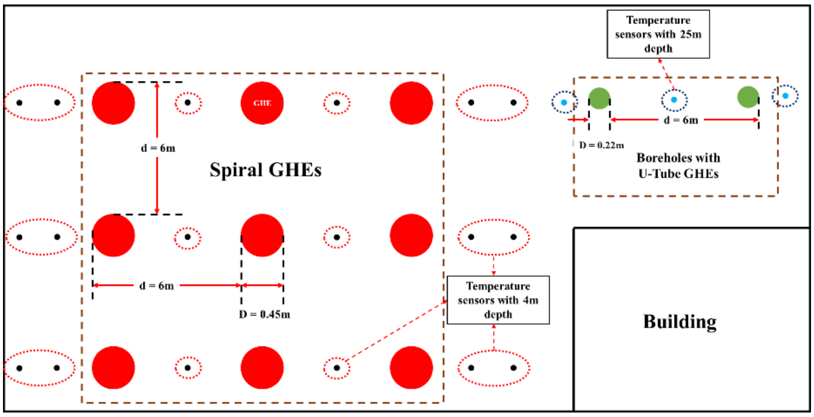
In this study thermal behavior of nine spiral GHEs is investigated experimentally and computationally. Energy of GT exhaust gasses is stored in ground through spiral GHEs and storage process in ground is simulated by COMSOL software based on validated models. Finally, the effects of storage process on thermal performance of nine spiral GHEs are analyzed.

2. EXPERIMENTAL AND COMPUTATIONAL STUDY

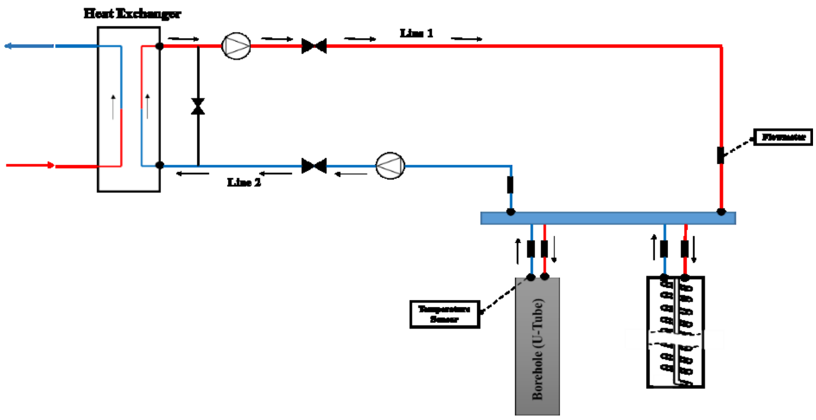
2.1 Experimental setup description

Although computational models are almost favorable among engineers due to their clearness and convenience, they need to be validated by experimental results or previously verified ones. In this paper to validate the accuracy of computational models, I compare its results with experimental ones. My goal in this study is investigating the effects of stored energy in ground on the thermal performance of nine spiral GHEs.

To investigate the thermal performance of the spiral GHEs and analyze their effectiveness on supplying heating/cooling demand of buildings, GSHP system of N.D.B. residence which is located in Tabriz, Iran is used. Fig.1 shows the schematic view of the entire experimental application area. In this application area we have different types of GHEs such as U-tube and spiral ones. As it is shown in this figure, application area consists of nine spiral (depth; 4m) and two U-tube (depths; 50m) GHEs. To record the temperature variations in ground during GSHP system operation, 21 temperature sensors (sensor type: Ds18b20) are embedded in ground with various locations and depths (18 sensors with 4m depth and 3 sensors with 25m depth). During the test, inlet and outlet water temperatures of each GHE are measured (by Pt100) as well as volumetric flow rate (by Z-4004 Flow Meter 2-20 GPM). Uncertainties for temperature and volumetric flowmeter are $\pm$ 0.1 ^{o}C and $\pm$3% respectively. Distance between spiral and U-tube GHEs are 6m. As it is shown in Fig.1b, a heat exchanger is used to keep the inlet temperature of GHEs in desired test or operation value. To investigate thermal performance of spiral GHEs in heating mode, fluid (mixture of water and glycol) is pumped into the spiral pipes in -3 ^{o}C and inlet/outlet temperatures are measured as well as volumetric flow rates in each GHE for 150 hours non-stop operation. In this study I only considered nine spiral GHEs. Furthermore, in application area, average temperature of ground along spiral GHEs and their surroundings is about 17^{o}C. Different properties of application area and working conditions are given in Table1.



(a)



(b)

Fig.1: (a) schematic top view of application area configuration (b) Schematic view of experimental setup

Fig. 2 represents the schematic view of spiral GHE which is used in this study. Different properties of the spiral GHE are shown on it additionally.

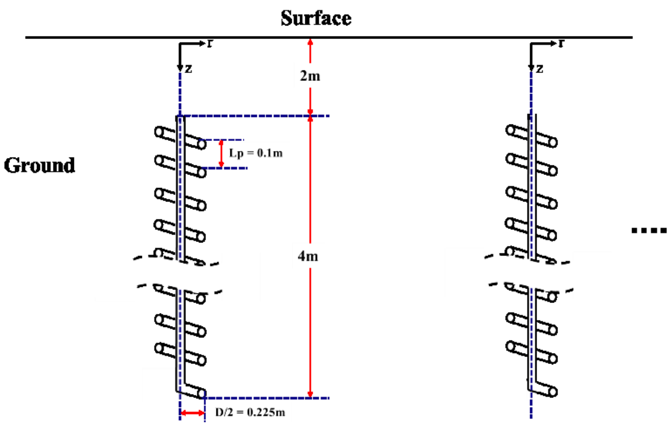


Fig.2: Schematic view of spiral GHE with different parameters on it.

Table 1: Parameters of application area

Parameters	Values	Definition
Thermal Properties of Ground		
ρ_g	2100	Density [kg m^{-3}]
c_{pg}	900	Specific heat capacity [J kg^{-1}K^{-1}]
k_g	1.8	Thermal conductivity [W m^{-1}K^{-1}]
Thermal Properties of Grout		
ρ_{gr}	1650	Density [kg m^{-3}]
c_{pgr}	950	Specific heat capacity [J kg^{-1}K^{-1}]
k_{gr}	0.9	Thermal conductivity [W m^{-1}K^{-1}]
Thermal Properties of Water-glycol mixture		
ρ_f [kg m^{-3}]	1036	Density [kg m^{-3}]
c_{pf} [J kg^{-1}K^{-1}]	3870	Specific heat capacity [J kg^{-1}K^{-1}]
Thermal Properties of PE		
ρ_{PE} [kg m^{-3}]	950	Density [kg m^{-3}]
c_{PE} [J kg^{-1}K^{-1}]	2300	Specific heat capacity [J kg^{-1}K^{-1}]
k_{PE} [W m^{-1}K^{-1}]	0.45	Thermal conductivity [W m^{-1}K^{-1}]
Geometric Properties of Spiral GHEs		
r_{pi}	0.014	Internal radius of PE pipe [m]
r_{po}	0.017	External radius of PE pipe [m]
L	4	Vertical length of spiral GHE [m]
D	0.45	Major diameter of spiral GHE [m]
L_p	0.1	Pitch length [m]
d	6	Distance between spiral GHEs [m]
Working Conditions		
$\dot{V}$	17	Average volumetric flow rate [L min^{-1}]
$\overline{T}_{ave}$	-2	Average fluid temperature [^oC]
$\overline{T}_o$	17	Initial temperature of system [^oC]
$\overline{T}_\infty$	17	Undisturbed uniform ground temperature [^oC]
t_{test}	150	Testing period [hour]

2.2 Results

Dehghan et al.(2016) work shows that, GSHP system which is conducted by nine spiral GHEs can be suitable and reasonable for the most of individual houses (independent villas). Therefor in this study I have decided to investigate the thermal performance of nine spiral GHEs much more exactly. In an experimental study as it was discussed in previous section temperatures of inlet and outlet fluid (water + glycol) are measured as well as volumetric flow rate. Thermal performance or heat transfer rate (HTR) amount (experimental amounts) of nine spiral GHEs is calculated by following expression;

$$\dot{Q}_{exp} = \sum_{N=1}^{9} \dot{V}_{wN} \rho_w c_{pw} \left(T_{iN} - T_{oN} \right) \quad (1)$$

$$\dot{q}_{exp} = \frac{\dot{Q}_{exp}}{L} \quad (2)$$

Where $\dot{Q}_{exp}$ is total HTR amount (W), $\dot{q}_{exp}$ is total HTR amount per length of GHE (W/m), L is length spiral GHE, $\dot{V}_{wN}$ is volumetric flow rate of Nth spiral GHE, T_{iN} and T_{oN} are inlet and outlet temperature of Nth spiral GHEs respectively.

Thermal behavior of nine spiral GHEs which are used as experimental study cases are simulated by COMSOL software (three dimensional, 3D simulations) and the results are validated by experimental ones. Boundary conditions of computational modeling are as follows;

$$T(0, r, \theta, z) = 17\ ^oC \quad (3)$$

$$T(t,\infty,\theta,z) = 17\ ^{o}C \tag{4}$$

$$T(t,r,\theta,\infty) = 17\ ^{o}C \tag{5}$$

$$T\left[t,D/2,\theta,z_{SP}(\theta)\right] = -2\ ^{o}C \tag{6}$$

where $z_{SP}(\theta) = L_p\theta/2\pi$ is the spiral relation while L_p is the pitch distance. Computational HTR values are also examined by;

$$\dot{Q}_{comp} = -k\int_{\partial V} \nabla T.\vec{n}dA \tag{7}$$

$$\dot{q}_{exp} = \frac{\dot{Q}_{mp}}{L} \tag{8}$$

where $\vec{n}$ is unit normal vector, ∂V is total peripheral area of the spiral GHE domain.

Computational and experimental results of nine spiral GHEs are given in Fig. 3. This figure shows that experimental and computational results are in good agreement and this verification confirm the accuracy of our modeling strategy.

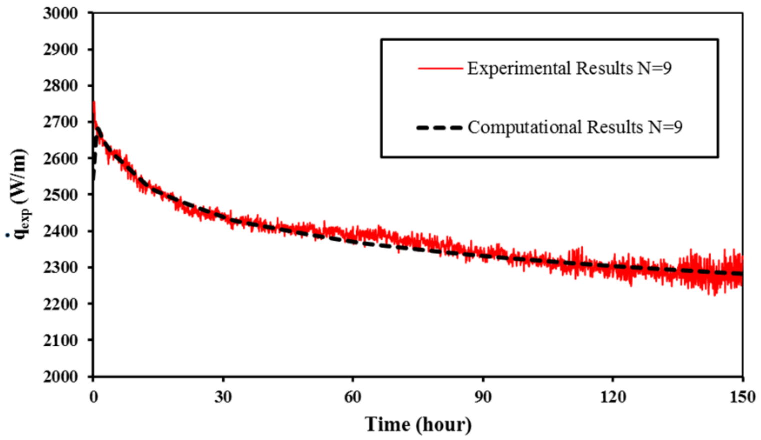


Fig. 3: Experimental HTR values per length of GHE for nine spiral ones (N=9, L=4m).

3. GAS TURBINE AND GROUND SOURCE HEAT PUMP COMBINATION

Since gases are exhausted turbine in high temperature, the high amount of heat can be stored in ground. In this section I have simulated the storage process by using validated models which are described in previous section.

In order to store GT exhaust gasses energy in ground I use eight spiral GHEs (L=6m, d=3m). Schematic top view of these spiral GHEs are shown in Fig.4. Red spiral GHEs shown in this figure are connected to GT and store energy of exhaust gasses in ground and blue ones are connected to heat pump system which are supplying heating demand of the building specially during cold climate. Figure 5 indicates schematic view of GT, absorption system and GSHP system combination.

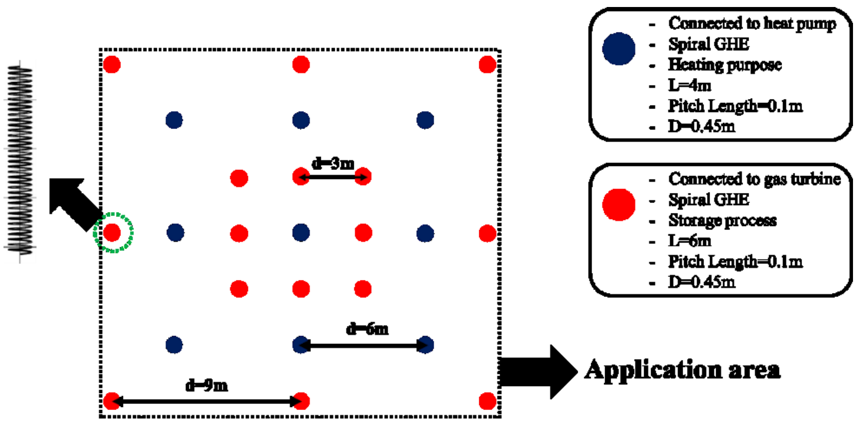


Fig. 4: Configurations of spiral GHEs used in heating and storage process

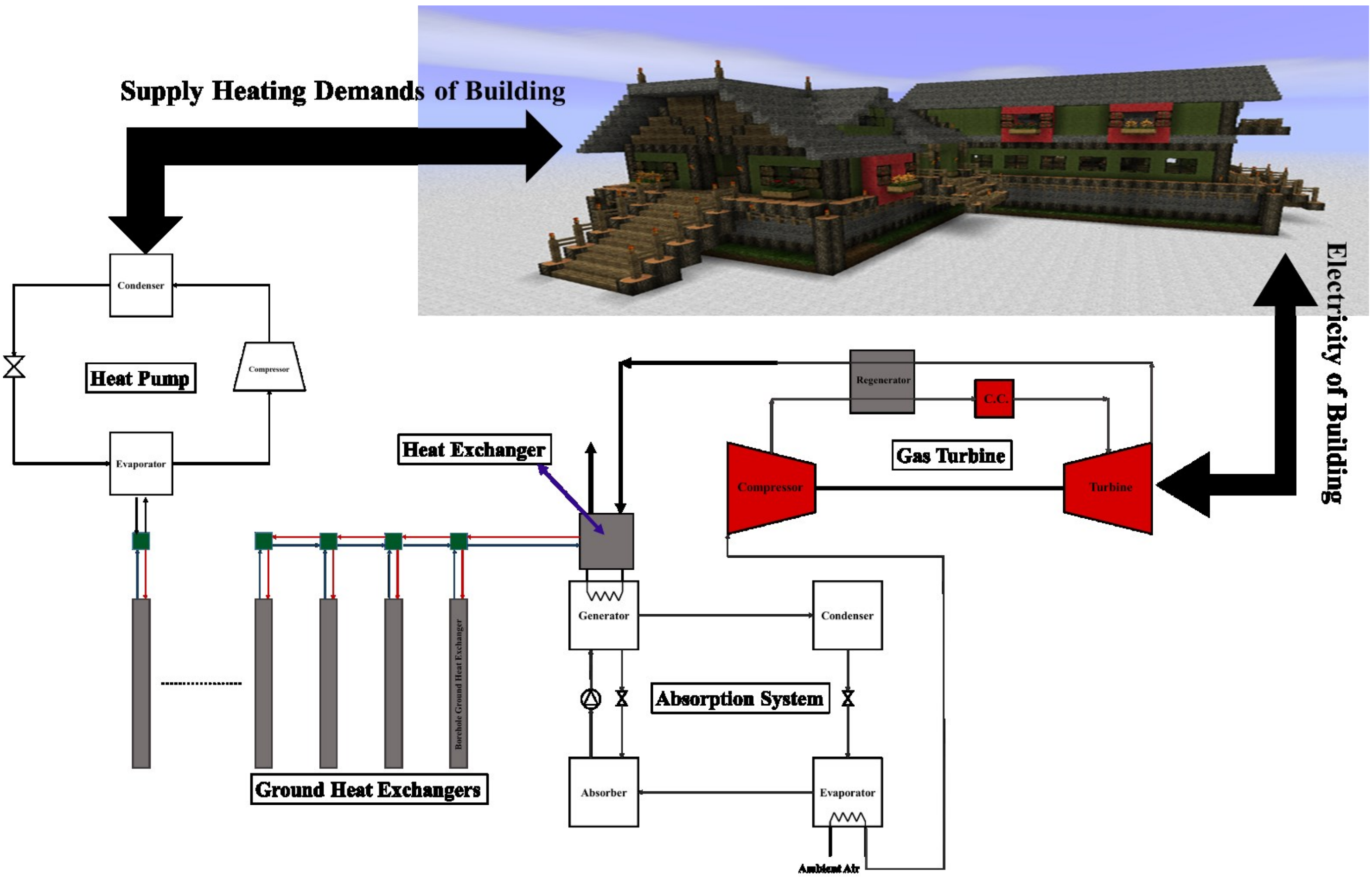


Fig. 5: Schematic view of system

To store thermal energy of exhaust gasses in ground, fluid (mixture of water glycol) is pumped into the heat exchanger which is embedded in the exit of GT. Pumped fluid is heated in heat exchanger up to the defined temperature and then pumped to the heat exchangers in ground. Fluid will transfer its energy (energy of exhaust gasses) to ground and this issue contributes to huge stored energy in ground. As it was discussed previously in this study I use spiral GHEs for storage process and average inlet and outlet fluid temperatures during storage process are assumed as 90 ^{o}C and undisturbed ground temperature is 17 ^{o}C. Fig. 6 shows thermal behaviors of spiral GHEs before, during and after storage process. As it is shown in this figure, before starting storage process, nine spiral GHEs are used for heating purpose and as you can see average inlet and outlet temperature is -2 ^{o}C. Heat transfer values ($\dot{q}_{exp}$) of this process for 150h was previously discussed in Fig.3. Second, during storage process, GHEs which are also shown in Fig.4 (red spiral GHEs) are connected to GT and thermal energy of GT exhaust gasses is stored in ground through 16 spiral GHEs. You can see in Fig.6(e-h) that, at the end of three months operation huge amount of heat will stored in ground. Finally, by completing storage process, nine spiral GHEs which are shown in Fig.4 and connected to heat pump system start extracting stored heat from ground. As you can see in Fig.6, final state of storage process (Fig.6h) is assumed as initial conditions of heat extraction process (Fig.6i) in computational modelling (only color ranges are different). It is important to note that again, spiral GHEs are simulated in 3D form and Fig.6 indicates thermal behavior of them from top view and in half plane of them (z=4m).

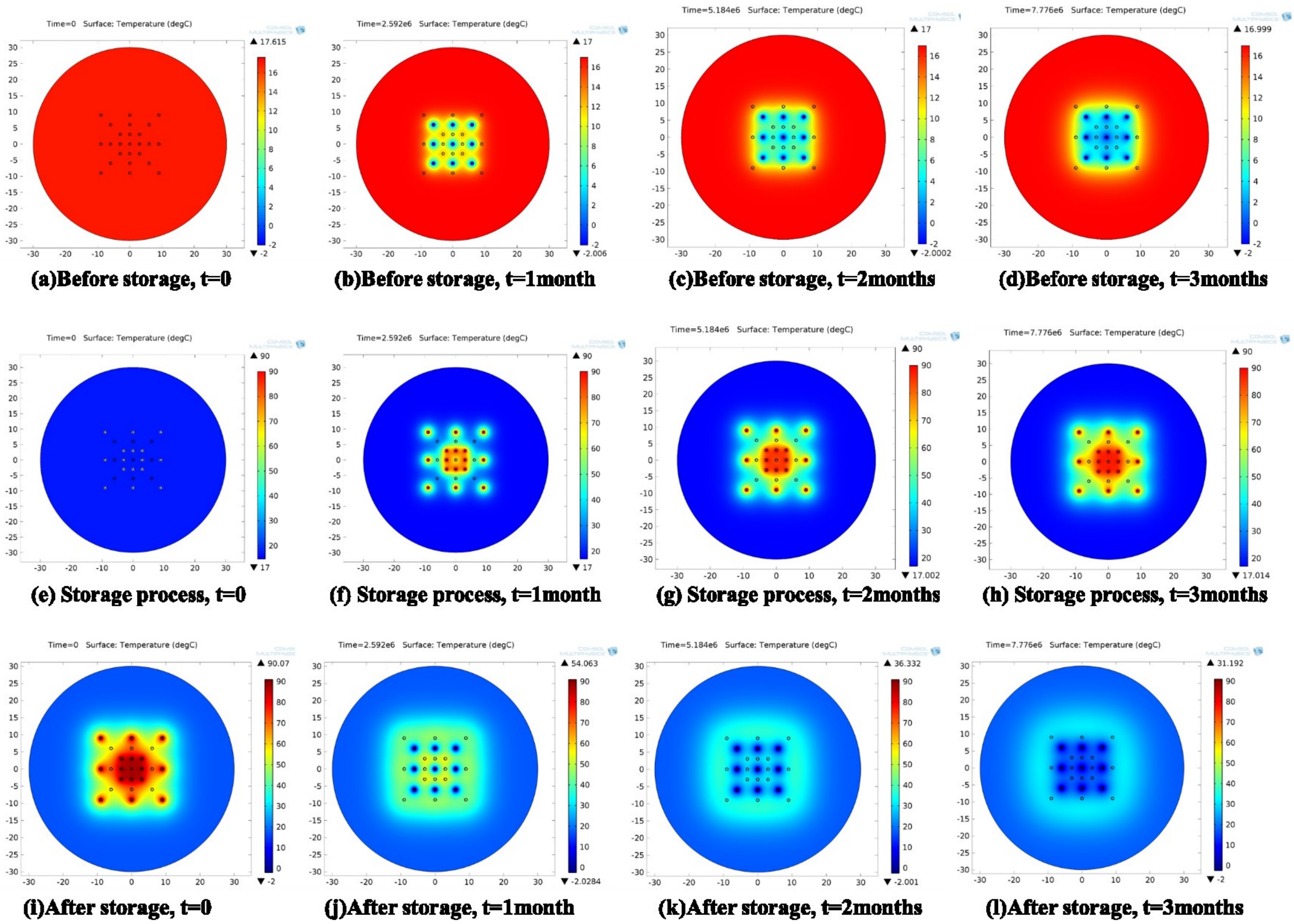


Fig. 6: Thermal behavior of spiral GHEs and temperature distributions in half plane of spiral GHE for different periods.

One of the most important goal of this study is to find the effects of storage process on thermal performance of nine spiral GHEs. In Fig.7 thermal performance of nine spiral GHEs before and after storage process is shown. HTR values before storage process are previously validated by experimental results (Fig.3). Results show that, thermal performance of nine spiral GHEs are highly increased after storage process. Average HTR values ($\dot{q}_{exp}$) are 1900 W/m and 6200W/m before and after storage process for 3 months non-stop operation. Furthermore, Effective space area that can be heated or cooled by nine spiral GHEs is calculated by following simple formula;

$$A\ [\mathrm{m}^2] = \frac{COP_h \times \dot{q}_{exp}\ [\mathrm{W/m}]}{(COP_h - 1) \times H_L\ [\mathrm{W/m}^2]} \times L[\mathrm{m}] \tag{9}$$

Where A is average space area of building that can be heated or cooled, COP_h is heating coefficient performance of heat pump, $\dot{q}_{exp}$ is average extracted heat from ground by GHEs, L is vertical length of spiral GHE, H_L is average heating load of building.

Here I assume that, $COP_h = 4.5$, $H_L = 75\ W/m^2$, $L = 6m$. By considering the values calculated for $\dot{q}_{exp}$ before and after storage process (1900 W/m and 6200W/m) , average space areas of building are calculated as 195 m^2 and 637 m^2 respectively. These values are calculated by considering nine spiral GHEs. Definitely by increasing number of GHEs HTR values are increased. In this study I try to show the effectiveness of using nine spiral GHEs which can be suitable for individual houses (Villas).

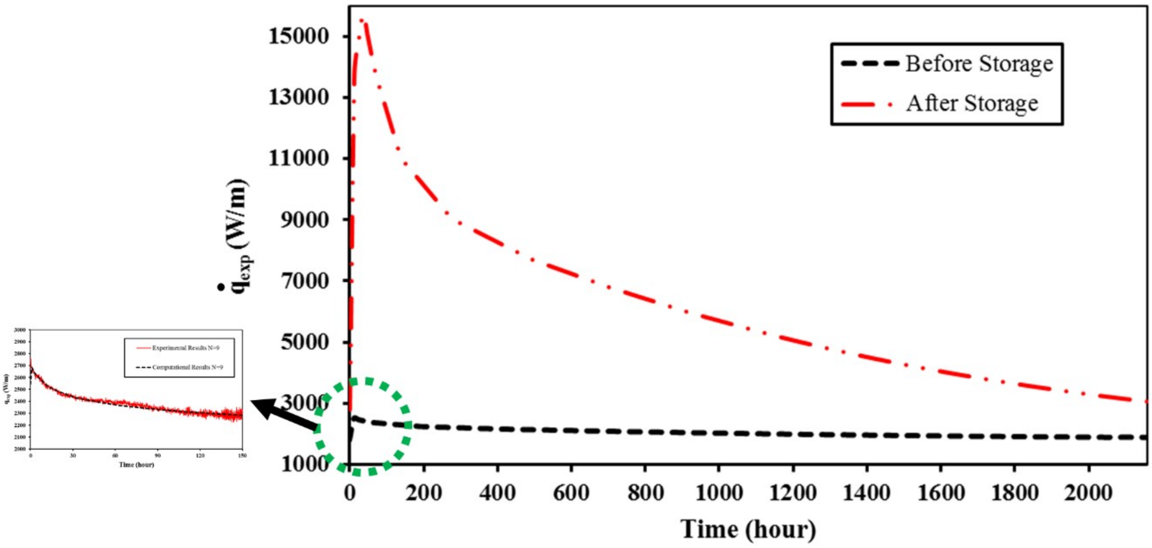


Fig.7: Thermal performance of nine spiral GHEs before and after storage process

Another important issue is stability and consistency of stored heat in ground. Figs.8 and 9 show the time in which system reach its initial states. Although computational studies are done in 3D form, to better show thermal behavior of ground around spiral GHEs temperature variations are shown from top view and in half plane of spiral GHEs (in z=4m). In Figs.8 and 9 I assume that system is switched off after storage process. In Fig.9 temperature values are average ones of maximum area which is affected in storage process.

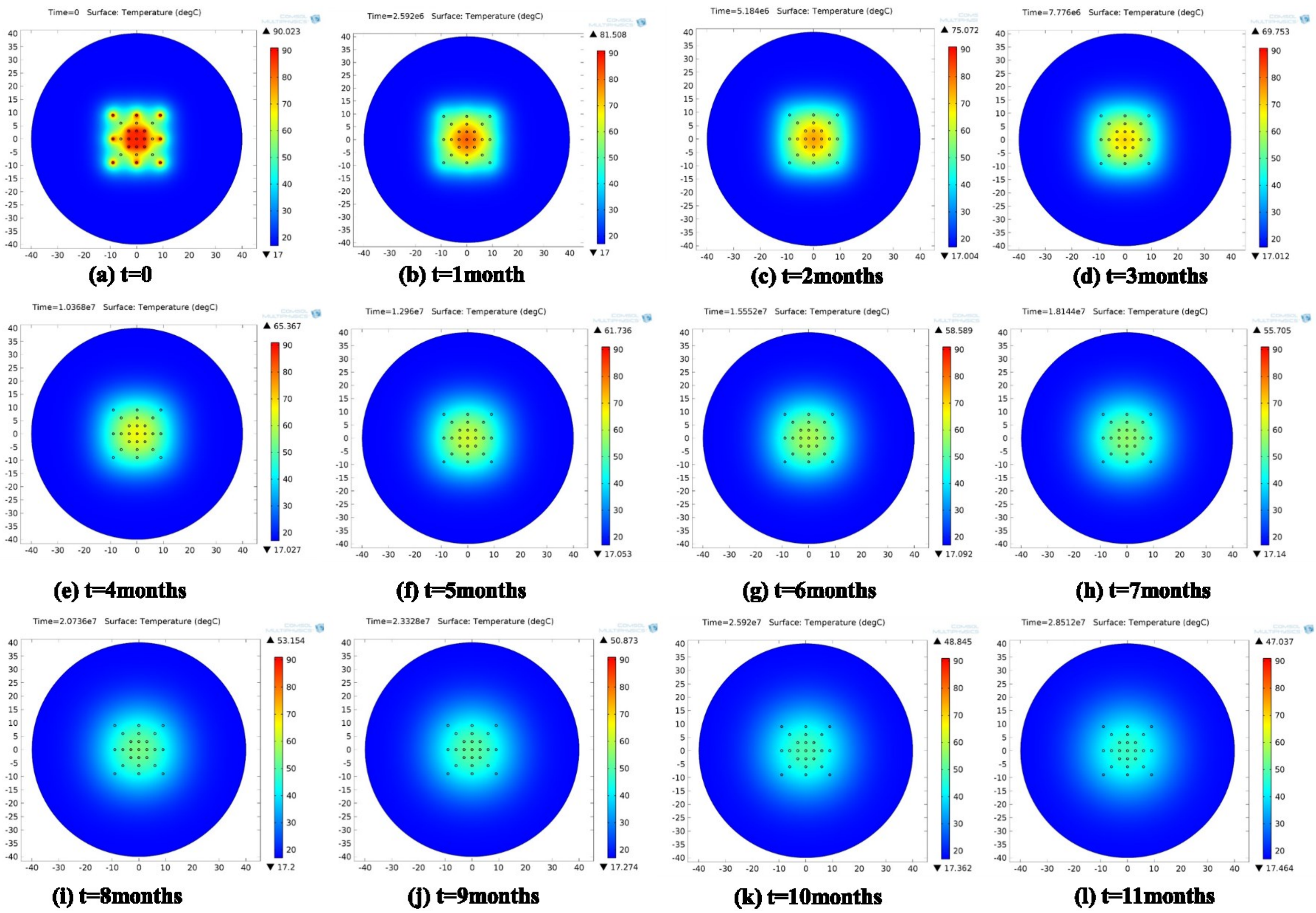


Fig.8: Discharge process

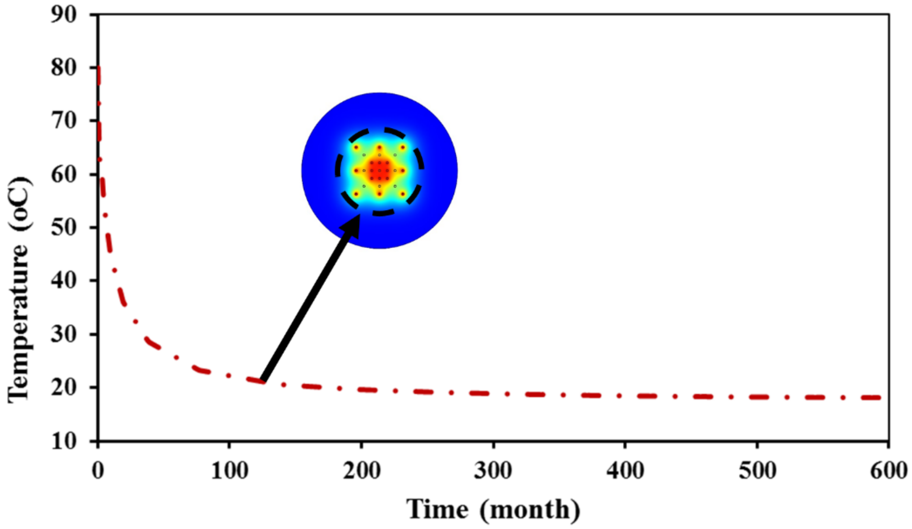


Fig.9: Energy discharge process

4. CONCLUSION

In this study I analyze thermal performance of nine spiral GHEs which are suitable for individual houses is investigated experimentally and computationally. Computational results are validated by experimental ones and this validation confirm the accuracy of our modeling. The main idea and purpose of this study is beneficial use of GT exhaust gasses. Gasses leave turbine in high temperature and they carry huge amount of energy. Here I try to manage and use this energy optimally. Partial exhaust gasses energy is stored in ground by using 16 spiral GHEs and heat transfer procedure in ground during storage process is simulated in 3D form by using COMSOL. Results show that, average HTR values ($\dot{q}_{exp}$) are 1900 W/m and 6200W/m before and after storage process for 3 months non-stop operation respectively. These values are calculated based on the most critical working conditions (3 months non-stop operation) and actual values are higher. Under actual working condition, GSHP system is working intermittently and this issue let ground temperature to be recovered.

Results of the study shows that, storing the energy of GT exhaust gasses in ground can become as an important issue. Storing this energy can highly reduce heating energy costs of GT surrounding buildings and also let buildings' designers (heating and cooling engineers of building) to use low number shallow GHEs instead of deep ones. In the future different research would be done on the topic of this study such as optimization of distance between GT and GHEs, different types of GHEs, methods of storing and etc. Additionally in the future studies I will investigate applicability of storage process experimentally and validate results of it by experimental ones.

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