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Performance assessment of ground source heat pump system integrated with micro gas turbine: Waste heat recovery

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ABSTRACT

Ground source heat pump (GSHP) systems become widespread due to their high efficiency in supplying heating demands of the buildings. Therefore, amount of extracted heat from ground through ground heat exchangers (GHEs) becomes as an important issue. This study consists of two main subjects, first, thermal capacity of an available application area which contains nine numbers of spiral GHEs is investigated experimentally and computationally. Existed operating system contains a GSHP and the nine spiral GHEs. In the second stage of the study, new operational system which consists of a micro gas turbine, a GSHP, sixteen spiral GHEs used for storing heat in ground and nine spiral GHEs used for extracting heat from ground, is suggested. Nowadays, micro gas turbines become popular based on their attractive features. However, large amount of exhaust gasses energy is wasted into the environment. In the new system, this waste energy is stored in ground through sixteen spiral GHEs during warm climate and then recovered in cold climate for supplying heating demands of the building. In this research, storage process of environmental waste energy in ground through spiral GHEs is simulated by COMSOL and thermal capacity of the developed application area is analyzed. Results show that, amount of extracted heat from ground through nine spiral GHEs is considerably increased after storage process.

1. Introduction

In a building, integration of the ground source heat pump (GSHP) system and micro gas turbine(s) is one of the best solutions for independent electricity generation and supplying heating demands of it [1,2]. Nowadays micro gas turbines become popular based on their attractive features such as low capital cost, direct coupling to the buildings, compact size, high flexibility, and fast starting and loading. In comparison with micro gas turbines, the exhaust gases of a simple gas turbine usually discarded to the surroundings at temperature above 500 °C with a significant losses of exergy. Regenerative heat exchangers and steam injection are common means of internal heat recovery. A regenerative process preheated the air exiting the compressor before entering the combustor. In steam injection method, the steam that is generated in a heat recovery steam generator unit using the thermal energy of the exhaust gas heat to water which then is injected into the combustor. The regenerative process reduces the amount of fuel that must be burned in the combustor for the same power output and steam injection increases the mass flowrate of the working fluid and thus the turbine work [1]. For industrial micro gas turbines, power rates of them are generally varied between 30 and 1000 kW. In these models exhaust temperatures are between 275 and 310 °C and exhaust gas flow rates are between 0.3 and 6.7 kg/s [3]. In comparison with other electricity production methods, the efficiency of gas turbine is low and environmental conditions are highly affecting the efficiency of the gas turbine. In the micro gas turbines, thermal energy of exhaust gases is wasted into the environment and it has side effects on human society such as air pollution, temperature rise, diminution of the ozone layer, and water pollution. [4]. In this case, several challenges are being considered in the field of environmental protection. The challenges facing concerned citizens and decision-makers are formidable; they focus upon the challenge to identify and implement long-term solutions in waste energy management that are environmentally harmless, socially acceptable and cost-effective [5]. Waste energy of exhaust gasses of micro gas turbines can be used for different purposes, first, it can be used for regeneration. Since the temperature of the exhaust gasses leaving the turbine is usually considerably higher than the temperature of the air, 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 gas turbine. Second, this energy can be used in a heat exchanger of generator of absorption refrigeration cycle to increase the thermal efficiency of gas turbine (for inlet air cooling). Third, during warm season (climate), turbine exhaust gases energy can be stored in ground and then reused

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Nomenclature

A	effective space area of building [m^2]
c_{pg}	specific heat capacity of ground
c_{PE}	specific heat capacity of PE tube
c_{pf}	specific heat capacity of fluid
d	distance between borehole
D	diameter of spiral GHE
k_g	thermal conductivity of ground
k_{PE}	thermal conductivity of PE tube
L	vertical length of Spiral GHE
L_p	pitch between helical turns
$\vec{n}$	unit normal vector
n	number of turns
N	number of GHE
$\dot{Q}_{comp}$	computational HTR value
$\dot{Q}_{\exp}$	experimental HTR value
r_{pi}	inner radius of PE tube
r_{po}	outer radius of PE tube
$\overline{T}_{ave}$	average fluid temperature
$\overline{T}_o$	initial temperature of system
T_s	storage temperature
T_∞	undisturbed uniform ground temperature
t_{test}	testing period
∂V	total peripheral area of the spiral GHE
$\dot{V}$	volumetric flow rate
z_s	depth of spiral GHE from surface
ρ_g	density of ground
ρ_{PE}	density of PE tube
ρ_f	density of fluid

Abbreviation

COP	Coefficient of Performance
GHE	Ground Heat Exchanger
GSHP	Ground Source Heat Pump
HTR	Heat Transfer Rate
PE	Polyethylene

during cold climate through GSHP system for district heating purposes. Since gases are leaving the turbine at high temperature, a huge amount of heat (energy) can be stored in ground. Since 1970, the seasonal thermal storage technology, as part of a solar district heating system, has been under exploration and inspection. Solar heat is collected by a large area of solar collectors and then transported to the central heating plant. The excess heat from solar panels, in summer, is directed to the thermal storage in ground. In the warm climate (season), the stored heat will be directed to the central plant to supply to the district heating system. Seasonal thermal energy storage stores heat in a sensible form. The key parameters that need to be dealt with, for finding the heat transfer and mainly losses through the storage are thermal properties of the storage medium, time of storage, storage temperature, storage geometry, and volume. In the seasonal thermal energy storage, especially in solar thermal district energy system, there is a significantly large amount of energy involved. Therefore, the ground has been found to be a satisfactory medium for storing such a large energy amount with a relatively low cost [6]. Main goal of this research is to store energy of micro gas turbine exhaust gasses in ground through spiral GHEs during warm season and then extract it in cold seasons. This energy can be stored in ground through different types of GHEs such as boreholes with U-tube pipes, slinky, and spiral. For example, in the borehole thermal energy storage method, the ground itself is the storage medium. This would be through vertical boreholes with U-tube pipes in the ground. The volume of the storage area is not exactly separated. Thermal properties of ground play an important role in specifying the thermal capacity of the storage medium. Rock and water- saturated soil are the most suitable geological formations. The vertical boreholes lengths are usually varied in the range of 30–100 m with approximately 3–4 m separation [7]. The borehole depths in recent installations have gone up to 200 m [8]. In the borehole, the heat is exchanged through a double or single U-pipes pipes. The pipe material is typically made of synthetic material like high-density polyethylene (PE) [8]. Although deep boreholes are favorable, their costs are high. Therefore, shallow GHEs such as spiral ones can be preferred due to their low cost and high efficiency. For GHEs, heat transfer process in ground is one the most important issues and it can be combination of conductive and convective processes. Therefore, simulation methods for combination of convective and conductive heat transfer becomes as an important problem [9].

Many researches have been done in the fields of “underground thermal storage”, “gas turbine waste heat recovery” and “modeling of GSHP system” [9–35]. As an example;

Cai et al. [10], suggested a new power and heat generation system which consists of CHP (combined heating and power) and GSHP system. In their work, experimental and theoretical methodologies are presented to investigate the operating performance of the system. They concluded that, a higher amount of heat in the flue gas can be recovered because of the reduced final temperature of the exhaust gases (from 140 °C to 50 °C) and most of the emission of sulfur to the environment can be eliminated. The simulation results of the whole system indicate that the new system makes better use of the flue gases, with total thermal efficiencies equal to 82.7% much higher than those of the reference system (73.8%).

Schmidt et al. [11], investigated central solar heating plants with seasonal storage in Germany. They described seasonal heat storage system as well as solar heating plants in detail and they concluded that, by the integration of seasonal heat storage, more than 50% of the annual heating demand for space heating and domestic hot water can be supplied by solar energy. Liu et al. [12] designed an experiment of solar seasonal storage coupling with ground source heat pump (GSHP) system. In their thermal storage experiment process, a system with 1500 m^2 solar thermal collectors and 580 sets of 120 m deep ground heat exchangers were taken into research. Their results showed that solar energy utilization efficiency achieved 50.2%. Jradi et al. [13] analyzed a soil-based thermal storage system by using solar driven air source heat pump system. Their work presented an analysis and evaluation of the performance of an underground soil-based thermal energy storage system for solar energy storage, coupled with a combined heat and power generation system. A combined PV-air source peat pump system is utilized to fulfil heating and electricity needs of a housing project in Odense, Denmark, in addition to charging the soil storage medium in summer months when excess electric power is generated. The stored heat is discharged in December and January to provide the space heating and domestic hot water demands of the residential project without the utilization of an external heating source. Another important thermal storage (energy saving) system is proposed by Ghezelbash et al. [14] presented a vertical ground-coupled heat pump system is for energy saving in a natural gas expansion plant. A remarkable feature of their proposed system is the type of energy resource used for preheating aim. the proposed system employs geothermal energy as a renewable energy resource for providing part of heating demand. Initially, the vertical ground-coupled heat pump system preheats the natural gas stream up to medium temperatures, then, gas stream passes through station heater and reaches the desired temperature. They presented attractive energy saving methods.

Kim et al. [15] analyzed a supercritical carbon dioxide Rankine cycle for waste heat recovery from a gas turbine. With respect to waste heat recovery, it is very important to maximize the net output power by