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Enhancement of gas turbine power output using earth to air heat exchanger (EAHE) cooling system

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ABSTRACT

The application of earth to air heat exchanger (EAHE) as an inlet air cooling system on gas turbine performance has been investigated. Transient, one-dimensional model was developed for predicting the thermal performance of EAHE. Gas turbine output power, efficiency and specific fuel consumption are assessed with application of EAHE. MATLAB program is developed for solving the discrete numerical equations. Damietta power plant is selected as case study. The output power and thermal efficiency of gas turbine increases by 9% and 4.8%; respectively. In addition the annual revenue will increase by $1.655 * 10^6$ \$ with payback period of 1.2 year.

1. Introduction

Gas turbines are constant volumetric flow rate machines. Its capacity is a function of compressor mass flow rate, typically controlled by inlet air temperature. The increase in inlet air temperature, especially pronounced in summer, causes a significant decrease in gas turbine output power. This takes place due to the reduction of air density and, thus, mass flow rate. It was found that the output power and efficiency reduced by 0.6% and 0.18%, respectively due to a 1 K temperature growth [1]. Gas turbine inlet cooling is one possible solution to solve this problem by reducing the compressor inlet air temperature. There are different methods used in gas turbine inlet air-cooling. These methods are divided into five categories including: evaporative cooling; high-pressure fogging; absorption chiller cooling; mechanical refrigerative cooling and thermal energy storage (ice and water storage) [2]. The utilization of these methods is different from plant to another according to several considerations such as climate conditions, thermo economic side and the temperature range of cooled air.

An extensive review of various inlet air cooling methods along with their advantages and drawbacks have been performed by Al-Ibrahim and Varnham [2]. For green sustainable energy, Najjar et al. [3] proposed using cascaded waste-heat recovery as inlet air cooling system. The system is a combination of a propane organic Rankine cycle (ORC) and a gas refrigeration propane cycle. The results showed that the net output power and overall efficiency increased by 35% and 50%, respectively due reducing inlet temperature from 45 °C to 15 °C. Popov [4] offered the concept of using solar energy to generate the electrical energy that used to power the mechanical chiller by photovoltaic panels. On another hand it is also proposed to generate steam which required as a heat source in absorption chiller. Zhang et al. [5] proposed utilization cryogenic energy from liquefied natural gas (LNG) as a method for inlet air cooling in gas turbine. It was concluded that the proposed air cooling method lead to increase the relative power and relative efficiency from 0.6% to 3.1% and from 0.3% to 0.5%, respectively above those of the traditional air cooling. The power and efficiency augmentation of Micro turbines (MGTs) using vapor compression method was presented experimentally by Comodi et al. [6]. It was found that the electric power an efficiency increased by 8% and 1.5%, respectively due to reducing the inlet temperature to ISO conditions at 15 °C. Najjar and Abubaker [7] investigated indirect evaporative cooling system (IECS) as a new form of inlet air cooling. The system is a combination of a humidifier with absorption or vapor compression cooling system. The results showed that the output power and efficiency increased by about 7.81% and 2.24%, respectively due to using IECS system. A complete optimization of fog inlet air cooling system for combined cycle power using a genetic algorithm was presented by Ehyaei et al. [8]. The optimization is based on the first law efficiency, the external social cost of air pollution for an operational system and energy cost. The results indicated that the optimization of the cooling system results in a great reduction in electricity price.

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Nomenclature

c	heat capacity (kJ/kg K)
D	diameter (m)
f	friction coefficient
h	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	pipe length (m)
M	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
T	temperature (K)
t	time (h)
U	overall heat transfer coefficient (W/m^2 °C)
W	power capacity (kW)
z	soil depth (m)

Greek symbols

γ	specific heat ratio (Cp/Cv)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
η	efficiency

Subscripts

a	air
c	compressor
f	fuel
g	flue gases
i	tube inside
in	input
o	tube outside
p	pipe
s	soil
t	turbine
th	thermal efficiency

Abbreviations

AF	air to fuel ratio
EAHE	earth to air heat exchanger
Nu	Nusselt number
Pr	Prandtl number
PVC	poly vinyl chloride
SFC	specific fuel consumption (kg/kW h)
Re	Reynolds number

Morini et al. [9] studied the capabilities of using liquid nitrogen spray for inlet air cooling in gas turbine for Integrated Gasification Combined Cycles (IGCC). The study based on using a thermodynamic model of an IGCC developed in a commercial code. It was found that the system did not prove to be profitable but the increasing of the ratio between the prices of electrical energy during peak and off peak hours can make the system profitable.

Supplementing to the previous research, the aim of this research is to investigate a new inlet air cooling system that suitable for hot and humid climate with low operating and initial cost. Therefore this paper is looking at one of the passive cooling strategies for inlet air cooling in gas turbine that are feasible for this objective through the Earth Air Heat Exchanger (EAHE) cooling system.

The earth to air heat exchanger EAHE or The Earth Air Tunnel (EAT) systems utilize the heat-storing capacity of earth, which uses ground as heat source or heat sink to accept or reject heat for full or partial heating/cooling of buildings. The EAHE has advantages of simplicity and low operating and maintenance cost. On another hand, it has some drawbacks like high initial investment cost and the cooling capacity is limited with the soil temperature [10]. Several experimental and analytical studies on the use of EAHE for heating and cooling of buildings have been found in literature. Most of these studies focused on the effect of the EAHE parameters on the performance such as pipe length, inner pipe diameter, inlet air velocity, depth of the buried pipe, the physical and thermal properties of the soil and the material of pipe used.

Sodha et al. [11] evaluated the performance of a large earth air tunnel system meant for heating and cooling of a hospital complex. It was found that the system has a daily average cooling capacity of about 512 kW h against 269 kW h heating capacity. Mihalakakou et al. [12] presented a parametric model to study the effect of the EAHE characteristics such as pipe length, inside diameter, air velocity and depth of the buried pipe on the thermal performance. Bojic et al. [13] evaluated the technical and economic performance of the EAHE for cooling and heating building which used 100% fresh air as cooling and heating medium during summer and winter. The results showed that this system is more energy and cost efficient in summer than in winter. A simple analytical model to evaluate the thermal performance of EAHE coupled with a greenhouse was developed by Ghosal [14]. It was concluded that the EAHE is more effective in winter than summer in IIT Delhi, India. Al-Ajmi et al. [15] developed theoretical model of the EAHE for predicting the outlet air temperature and cooling capacity for domestic buildings in desert climate. It was found that this system could reduce the cooling demand by 30% over the peak summer season in a typical house. Wu et al. [16] provided a transient and implicit model based on numerical heat transfer and CFD analysis for evaluation of the cooling capacity of EAHE. The results indicated that the system could achieve daily cooling capacity up to 74.6 kW h. Lee and Strand [17] carried out a parametric analysis to study the effect of pipe length; pipe diameter; air flow rate and depth of the buried pipe on the overall performance of EAHE under various conditions. It was concluded that the better performance could be achieved in the case of long pipe with smaller diameter and air velocity. The performance of EAHE assisted by an evaporative cooler at outlet was investigated by Bansal et al. [18]. The analysis was carried out individually for 8760 h of the year. It was found that a simple EAHE could provide a cooling effect of 4500 MJ, whereas 7609 MJ of cooling effect was achieved by the integrated EAHE evaporative cooling system during summer months. Misra et al. [19] studied the variation of derating factor of the EAHE due to the effect of the following parameters namely; time duration of continuous operation, pipe length, inner pipe diameter, inlet air velocity and thermal conductivity of soil using CFD analysis. The results showed that the increasing in flow velocity leads to deterioration in thermal performance of EAHE system. Diaz-Mendez et al. [20] presented a simulation of a thermodynamic model of an earth–air heat exchanger which used along with a PID controller for estimating savings in energy consumption. It was concluded that the energy consumption can be reduced up to 87% with the PID control. Ramírez-Dávila et al. [21] presented a numerical analysis of conjugate heat transfer in two dimensional between the pipe and the soil for three cities in México. It was found that the use of EAHE system is suitable for cooling or heating of buildings in regions where the thermal inertia effect in soil is