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Thermodynamics and emission analysis of a modified Brayton cycle subjected to air cooling and evaporative after cooling

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ABSTRACT

In the current research, a gas turbine fueled by natural gas and integrated with the reversed Brayton cycle for cooling the intake air then evaporation was studied. The performance of the proposed cycle was assessed theoretically from energetic and environmental aspects. To achieve this, first a validation study has been performed based on temperature and emission analysis of a gas turbine model. Second, detailed energy analysis was conducted to identify the causes and locations of thermodynamic imperfection in terms of 1st and 2nd law efficiencies. Third, analytical relations for the theoretical measurement of two key emissions namely; Nitrogen Oxides and Carbon Monoxides were studied and applied. The effects of important influencing parameters such as the ambient temperature, ambient relative humidity, extracted mass rate and equivalence ratio on energy and environmental performance of the cycle was investigated. It was found that the proposed gas turbine cycle can bring down the emission levels to the regulatory standards (less than 35 ppm). It was also able to increase the power output by 31% with a slight drop in its efficiency. Therefore, the results of this research may be used to determine the range of operating parameters at which the gas turbine could be operated which can provide a considerable reduction in the emissions while maintaining a higher performance.

1. Introduction

Energy is a key for economic growth of every nation and energy conversion from given into desired form in an efficient and environment friendly manner is still a challenge. Majority of power production comes from the combustion of fossil fuels which results in the fast depletion of fossil fuel reserves and environment. This creates a need to enhance the fuel efficiency utilization and emissions reduction. Generally, GT performance is affected by the weather conditions [1]. The climate of the Kingdom of Saudi Arabia and in the Gulf region is harsh and extreme especially in the summer and can rise up to 53 °C during summer [2]. Having a desert climate in the Kingdom, large ambient temperature variations are observed on daily and seasonal basis. In hot regions, the warm air taken by the air compressor will decrease the air density, consequently the air flow rate will be reduced resulting on decreasing the net power output below ISO standard [3]. Furthermore, GT power output will be reduced by 5–9% for every 10°C increase in ambient temperature above the ISO standard [4]. There are few methods to obtain air cooling at the intake section of the air compressors: evaporative cooling by spray water or by mechanical or refrigeration method. Each of these methods have its advantages and disadvantages. Mechanical refrigeration systems reduces the inlet air pressure and adversely affects the overall output as a result of the large power consumption for cooling. Evaporative cooling methods are very low cost methods of inlet air cooling. However, the performance of evaporative cooling is limited by the relative humidity of ambient air. The focus of this study is the spray water evaporative cooling method. The key features of this method are well and intensively demonstrated in the following section. Literature review on former relevant studies were performed to support the novelty of the current work.

The intake air density decreases when the ambient temperature increases. This causes a decrease in the intake mass flow rate as the temperature increases and hence, the power developed by the gas turbines because gas turbines operate at constant speed and constant volume flow rate [5]. The increase in ambient relative humidity also reduces the density of air, as vapor is lighter than the dry air as reported by Liu and Karimi [6,7] while simulating the combined cycle gas turbine power plans. Therefore, the power developed, and thermal

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Nomenclature

a_1, a_2, ..	coefficients of polynomial determining specific heat
C_p	specific heat, kJ/kg-K
$\overline{C}_p$	molar specific heat, kJ/kg-K
e_x	specific exergy, kJ/kg
g	Gibbs function, kJ/kg
h	specific enthalpy, kJ/kg
$\overline{h}$	molar specific enthalpy, kJ/kmol
$\dot{I}$	irreversibility rate, kW
M	molecular weight, kg/kmol
$\dot{m}$	mass flow rate, kg/s
n	number of moles, kmol
p	pressure, kPa
p_r	extracted pressure ratio, kPa
$\dot{Q}$	heat transfer rate, kW
R	gas constant, kJ/kg-K
$\overline{R}$	universal gas constant, kJ/kmol-K
s	specific entropy, kJ/kg-K
$\overline{s}$	molar specific entropy, kJ/kmol-K
T	temperature, K
$\dot{W}$	work done rate, kW
v	specific volume, m^3/kg
$\dot{X}$	flow exergy rate, kW
x, r	pressure ratios
y	mole fraction
α	mass rate ratio
β	percentage of pressure drop
γ	polytrophic ratio
δ	percentage of bypass air
Δ	difference of a quantity
$\Delta\overline{H}_r$	molar enthalpy of reaction, kJ
ε	effectiveness
ϕ	equivalence ratio
η	efficiency
λ	relative humidity
λ_0	ambient relative humidity
ω	humidity ratio, kg/kg of air
$\overline{\omega}$	molar humidity ratio, kmol/kmol of air
()	'a function of' a quantity

Abbreviations

AC	after cooler
Com	compressor
CC	combustion chamber
Ex	expander
gen	generator
HE	heat exchanger
HPGT	high pressure gas turbine
HPC	high pressure compressor
LPC	low pressure compressor
LHV	lower heating value of the fuel kJ/kg
LPGT	low pressure gas turbine
MC	mixing chamber
Re	recuperator
RH	reheater
TIT	turbine inlet temperature, K
WH	water heater

Subscripts

0	ambient condition
1,2,3	state points
a	air
av	average
ch	chemical
f	fluid
g	gas
i	iterating parameter
in	input
mix	mixture
out	output
P	products
ph	physical
R	reactants
r	reaction
sat	saturation condition
v	vapor
W	work
w	water

efficiency of gas turbines are adversely affected by the atmospheric temperature and relative humidity. During the period of peak power demand, it is seen that 1°C rise in atmospheric temperature may reduce the gas turbine power output by 0.57% [8]. It is reported that up to 35% power output may be enhanced if inlet air cooling technique is deployed [9]. Dawoud et al. [10] after incorporating four techniques to achieve inlet air cooling namely evaporative cooling, fogging cooling, absorption cooling and vapor compression cooling, showed that for a natural gas operated combustion turbine, reduction in compressor inlet temperature from 45°C to 15°C, enhanced the power output from 69 MW to 84.4 MW. It means the power output is increased by 20% by cooling the incoming air considerably. This shows the compressor inlet temperature is essential to reduce for increasing the power augmentation in gas turbines at peak summer. Various inlet air cooling technologies have been applied and the outcomes are well reported in the literature. Alhazmy et al. [4] employed the methods of mechanical chilling and evaporative cooling to reduce the inlet temperature of air going to gas turbines that operate in extreme ambient conditions in Jeddah. Power output with the mechanical chilling increased by 6.77% versus 2.57% for the spray evaporative cooling. Al-Amiri and Zamzam [11] investigated the combustion gas turbine where compressor inlet air is cooled through both refrigerated and evaporative cooling systems in view of assessing the net power increase. Their findings reveal that evaporative inlet air cooling method is suitable for the power increase of 8% to 15%. Furthermore, the advantages of inlet cooling has an upper limit below 280 K when the vapor present in the air could freeze and form ice crystals which can affect the performance of the compressor as long as the air temperature reduces [12]. Evaporative after cooling is injecting water at the exit of the compressor. This water gets converted to vapor and is absorbed by the air. This will reduce the air temperature but increases the mass flow rate within the turbine which raises the net output power. If a Recuperator/heat exchanger follows the compressor, then the heat recovered from the exhaust gases would be more with evaporative after cooling compared to no water injection [13]. It is revealed that, employing evaporation after cooling could increase the power of the gas turbine by as much as 55% with a slight increase in the efficiency [14]. Mohapatra and Sanjay [15] studied the air transpiration cooled gas turbines subjected to evaporative inlet cooling from energetic analysis point of view. Their analysis reveals that such configuration of gas turbines increases the specific work by 9.98% and efficiency 4.34%, respectively. Naserian et al. [16] performed new exergy analysis of a regenerative closed Brayton cycle to investigate the optimal performance of the system. The study revealed that at a specified dimensionless mass flow parameter, exergy overestimation causes about 31% lower estimation of the 2nd law efficiency. Haseli [17] performed an optimization analysis of a