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Parametric investigation of a modified gas turbine power plant

Mohanad Abdulazeez Abdulraheem Alfellag

Mechanical Eng. Dep., University of Anbar, Iraq

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ABSTRACT

In this paper, a parametric study of a gas turbine power plant with the implementation of intercooling, reheating and regeneration is proposed. Thermal efficiency and the specific fuel consumption are evaluated with respect to various parameters including intercooler effectiveness, regenerator effectiveness, ambient temperature, compression ratio, reheating temperature, turbine isentropic efficiency, and compressor isentropic efficiency. The analytical formulas to evaluate the thermal efficiency are derived taking into consideration the operation conditions. MATLAB software is used to build the model. Modeled results show that the thermal efficiency increases with the increase of intercooler and regenerator effectiveness, increase of reheating temperature, decrease of ambient temperature, increase of turbine and compressor efficiencies. Thermal efficiency rises with compression ratio up to 2.2, and then it starts to decrease with increasing of compression ratio. Specific fuel consumption decreases with the decrease of ambient temperature, intercooler and regenerator effectiveness. SFC decrease with compression ratio up to 2.2. Then, it rises with the rise of compression ratio. Comparison between simple gas turbine and current model is presented also, and results indicated that at any ambient temperature, the thermal efficiency of the proposed model is higher than the simple cycle within 16–20%.

1. Introduction

Gas turbine has been used widely in the power industry and this due to its compactness, low weigh and low capital cost [1]. During the last 20 years, gas turbine technology had grown significantly, and this growth is accounted for increasing in compression ratio, new coatings and the development of materials technology. In general, Gas turbine power plants that work on simple cycle have a thermal efficiency of 16–23% due to the waste of high temperature exhaust gases [2]. Thermal efficiency increases with the rise of turbine inlet temperature. However, metallurgical limitations do not allow the temperature to be above 1200 K [3]. Therefore, in order to increase the performance of the plant, some modifications can be applied to the simple cycle such as intercooling, reheating, and regeneration. In intercooling cycle, the compression is performed in two stages and that requires two compressors; low-pressure compressor and high-pressure compressor with intercooler between them. The work input for the compressors will be reduced. Thus, the work net of the plant will be increased. When intercooling is used, a source of cooled water should be available [4]. Thermal efficiency may not be increased because of the increased value of added heat if the intercooling alone is used [5]. Two turbines and two combustion chambers are required in the reheating cycle; high-pressure and low-pressure turbines. The combustion gases expand in the first turbine and get heated by the second combustion chamber and then expand in the second turbine. Thus, the output power will increase, but more fuel will be required [2].

The temperature at the exit of the turbine is often above the ambient temperature, and a great amount of energy is thrown away to the surrounding. This lost energy can be utilized by using it to preheat the air leaving the compressor and before entering the combustion chamber through a heat exchanger called a regenerator. Therefore, required amount of fuel which will be burnt inside the combustion chamber will be reduced and hence increasing the thermal efficiency [5]. The additional added heat due to using intercooling and reheating is overcome by utilizing the regenerator. As a result, the overall thermal efficiency of the cycle will increase Many studies have been developed and carried out regarding the performance of gas turbine power plant. Rahman et al. [6] carried out a study on the performance of regenerative gas turbine taking into account all the related parameters. Thermal efficiency was found to be increasing with the increase of regenerative effectiveness, turbine and compressor efficiency. On the other hand, thermal efficiency decreased with the increase of ambient temperature and compression ratio. Ibrahim et al. [7] conducted a parametric study of intercooled gas turbine. Output power and thermal efficiency are calculated with respect to the cycle temperatures and compression ratio. Results indicated that increasing

E-mail address: mohanadheete@uoanbar.edu.iq

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Nomenclature

T	temperature
P	pressure
X	intercooler effectiveness
r_p	total compression ratio
r_{p_c}	compression ratio for compressor
r_{p_T}	compression ratio for turbine
Cp_a	specific heat for air
Cp_g	specific heat for gas
W_c	compressor work
W_T	turbine work
Q_{add}	heat added
G	generator

Greek symbol

ϵ	regenerator effectiveness
η_{th}	thermal efficiency
γ	heat capacity ratio

Subscripts

H.P. T	high pressure turbine
L.P.T	low pressure turbine
H.P.C	high pressure compressor
L.P.C	low pressure compressor
C.C	combustion chamber
AFR	air to fuel ratio
CV	calorific value of fuel
SFC	specific fuel consumption

turbine inlet temperature, intercooler effectiveness, and compression ratio would increase the thermal efficiency of the intercooled gas turbine.

Wang et al. [8] used the theory of finite-time thermodynamics to study the effect of some parameters on the performance of an irreversible closed intercooled regenerated Brayton cycle coupled to variable temperature heat reservoirs. These parameters include regenerator, intercooler, and hot and cold side heat exchangers) effectivenesses, efficiency of turbine and compressor, the pressure recovery coefficients the heat reservoir inlet temperature ratio and the cooling fluid in the intercooler and the cold side heat reservoir inlet temperature ratio. Pressure drops in the cycle are assumed to be negligible when the heat transfer between the fluid and heat reservoir ideally occurred. Wang et al. [9] presented a study of power optimization of optimal heat conductance distribution and optimal intercooling pressure ratio for power optimization of an irreversible closed intercooled regenerated Brayton cycle utilizing finite-time thermodynamics (FTT) theory. The study used optimal intercooling pressure ratio and optimal heat conductance distribution for the four used heat exchangers which are intercooler, regenerator, hot and cold side heat exchangers. This paper results that there is a pressure ratio which lead to doubling the output power.

Sánchez-Orgaz et al. [10] performed an analysis on the effect of regenerator effectiveness on the performance of multi-step solarized Brayton cycle. The model assumes an arbitrary number of turbines and compressors, regeneration, and several realistic irreversibility sources. The main results show that for a simple Brayton cycle coupled with concentrating solar system, the increase in regenerative effectiveness does not improve the thermal efficiency of the cycle. Regenerative effectiveness has more noticeable effect on the thermal efficiency when utilizing two compressors and two turbines. Ahmed et al. [11] presented a study for improving the performance of gas turbine using two scenarios; intercooling and regeneration. Simulated results presented that increasing pressure ratio and turbine inlet temperature would increase the performance of intercooled cycle. When increasing regenerative effectiveness, compressor and turbine efficiencies, the output power and thermal efficiency increase. Thermal efficiency increases with the increasing of compression to 5. After that, it starts to decrease with the increasing of compression ratio. However, in simple cycle, thermal efficiency always rises with the increase of pressure ratio.

Chen et al. [12] applied the theory of finite-time thermodynamics (FTT) to analyze the performance of an irreversible closed intercooled regenerator Brayton-cycle coupled to constant-temperature heat reservoirs. This study used some parameters including intercooler, heat exchangers, and regenerator effectivenesses, efficiency of turbine and compressor, and temperature ratio of heat reservoir. The study results that maximum output power or maximum efficiency occurs when the intercooling pressure reaches the optimal value. Sanjay et al. [13] carried out an analysis of intercooled combustion –turbine based combined cycle power plant. The pressure ratio of intercooling has been studied to maximize the cycle performance. At lower intercooling pressure ratios, the thermal efficiency is maximized. However, at higher values of intercooling pressure ratios, the cycle power output is maximized. The optimum performance of the plant including efficiency and work output occurs at intercooling pressure ratio of 4 with overall compressor pressure ratio of 34. Intercooled combined cycle enhances the plant work by 20% compared to the basic cycle.

Tyagi et al. [14] proposed a model of intercooled-regenerative-reheat gas turbine. The thermal efficiency and work output are maximized as function of cycle temperatures for a set of working conditions. The work power output increases with the increase of effectiveness of heat exchangers, heat capacitance rate of external reservoirs, and efficiency of the cycle components. In addition, there are optimum values of intercooling and reheating pressures which give maximum efficiency. However, these values are lower than those corresponding to optimum work output. Mohammed et al. [15] proposed a thermal analysis of combined reheat regenerative gas turbine cycle using MATLAB software. Overall pressure ratio, turbine inlet temperature, ambient temperature and regenerative effectiveness were taken as parameters. The study showed that increasing regenerative effectiveness would increase the thermal efficiency and decrease the heat required in the burner. Patil et al. [16] conducted a thermal performance study of reheat, regenerative, intercooled gas turbine cycle. Calculations were performed applying various parameters and conditions. Thermal efficiency decreases with the rise of ambient temperature and decrease of regenerative effectiveness. Specific fuel consumption decreases up to compression ratio of 10, then, it starts to rise with the rise of compression ratio. Moreover, with rising isentropic compressor and turbine efficiencies, thermal efficiency also increases.

In this study, a gas turbine power plant model is built applying the three modifications; intercooling, reheating, and regeneration. Thermal performance is analyzed by taking a wide range of parameters including intercooler effectiveness, regenerative effectiveness, ambient temperature, compression ratio, reheating