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Performance Analysis for Regenerative Brayton Cycle at Various Ambient Temperature

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ABSTRACT
Gas turbines are used for power generation, Brayton cycle is the basic cycle for gas turbine operation and developing the alternative cycles, The regenerative Brayton cycle is a developed cycle for the basic Brayton cycle with higher thermal efficiency at low to moderate pressure ratios. In this paper, the performance of a Regenerative Brayton Cycle at varies ambient temperatures were computationally evaluated in terms of thermal efficiency, net power, and specific fuel consumption. The analysis was performed with utilizing input values such as pressure ratio, regenerator effectiveness, and turbine inlet temperature, the results show that the thermal efficiency and output power increase with ambient temperature decrease while the specific fuel consumption increase with ambient temperature increase.

Key words- Brayton Cycle, Regenerative, Gas Turbine, Ambient Temperatures, thermal efficiency, net power, specific fuel consumption.

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I. INTRODUCTION

Brayton cycle is one of the most common thermodynamic cycles known for a basic cycle for gas turbines which can be used to generate power in power plants or generate thrust in airplanes engines.

The Brayton cycle was first proposed by George Brayton for use in the reciprocating oil-burning engine that he developed around 1870 Since then, has been developed with the time. the gas turbine has experienced phenomenal progress and growth since its first successful development in the 1930s. The early gas turbines built in the 1940s and even 1950s had simple-cycle efficiencies of about 17 percent because of the low compressor and turbine efficiencies and low turbine inlet temperatures due to metallurgical limitations of those times. Therefore, gas turbines found only limited use despite their versatility and their ability to burn a variety of fuels [1].

Research in terms of analyzing the performance of the Brayton cycle has been done by M. Goodarzi et al.[2] they analyzed the performance of modified regenerative Brayton and inverse Brayton cycle by partially bypassing the airflow entering the regenerator, the influence of the bypass mass flow ratio on thermal efficiency and net output power of the modified cycle has been studied for varieties of compressors' pressure ratios. A new regenerative Brayton cycle made by Goodarzi,[3] an energy analysis conducted on ideal cycles to compare them from the first law of thermodynamics viewpoint. Comparative analyses showed that the new regenerative Brayton cycle has higher thermal efficiency than the original one at the same pressure ratio, and also lower heat absorption and exhausting heat per unite output power. Memon et al.[4] conducted thermo-environmental, economic and regression analyses of simple and regenerative gas turbine cycles the results of the parametric study have shown a significant impact of operating parameters on the performance parameters, environmental impact and costs. An energetic analysis of a gas turbine with regenerative heating using turbine extraction at intermediate pressure was conducted by Ziołkowski et al.[5] the simple Brayton cycle of a commercial GT8C gas turbine has been modeled, the gas turbine cycle, advanced has been optimized. The main idea of modification is based on the extraction of exhaust gases from a gas turbine for air preheating before it enters the combustion chamber. Analysis of a Regenerative Gas Turbine Cycle for Performance Evaluation was studied by Ranjan and Tariq [6] at various parameters The most important parameter which has been covered is the various polytropic efficiencies of the compressor. The power output and thermal efficiency are found to be increasing with the regenerative effectiveness, and the compressor and turbine efficiencies. Erdem and Sevilgen [7] performed a study about the Effect of ambient temperature on the electricity production and fuel consumption of a simple cycle gas turbine in

Turkey. Basrawi et al.[8] studied the Effect of ambient temperature on the performance of the micro gas turbine with a cogeneration system in a cold region. Sa and Al Zubaidy [9] find an empirical relationship between the gas turbine's ability to generate power when exposed to site ambient conditions, such as the ambient temperature, which differs from ISO conditions. Saif and Tariq [10] performed an analysis for a simple open cycle gas turbine power plant which is situated at Uran in district Raigad of Maharashtra, India is carried out at varying the ambient temperature and pressure ratio and a comparison is carried out from the stipulated ISO conditions. Gautam et al. [11] they study the performance analysis of the simple Brayton cycle, the net power and total efficiency of the system are chosen as the performance criteria. The variable parameters selected for analysis are the compressor pressure ratio and ambient temperature. The other variables are assumed constant. Omar et al. [12] investigated the effect of ambient air temperature, regeneration effectiveness, and compression ratio on the Regenerative Brayton cycle thermal efficiency.

The comprehensive research works that have been done for the Brayton cycle in terms of performance analysis mentioned in the literature review reveals the importance of the Brayton cycle hence, in this present study the performance of a Regenerative Brayton Cycle was evaluated at wide range of ambient temperature (T_1).

II. THERMODYNAMIC MODEL

In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor. Therefore, the high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger, which is also known as a regenerator or a recuperator. A sketch of the gas-turbine engine utilizing a regenerator and the T-s diagram of the new cycle are shown in Fig. 1 and 2, respectively[1].

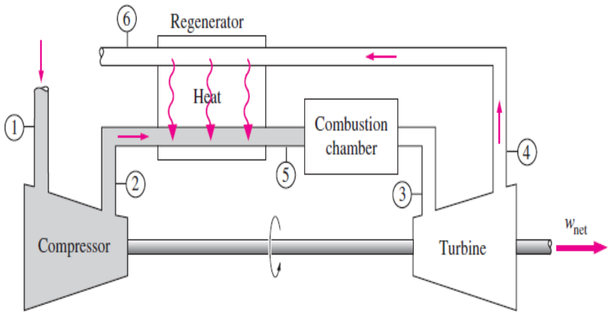

Fig.1 A gas-turbine engine with regenerator[1] .

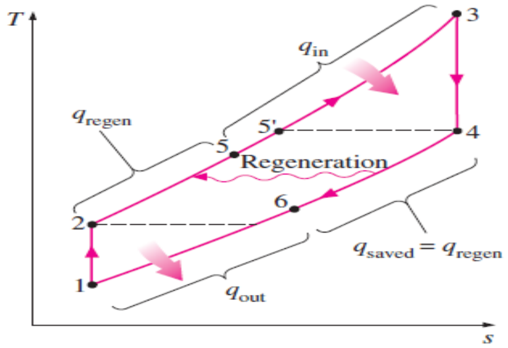

Fig.2 T-s diagram of a Brayton cycle with regeneration [1].

The thermal efficiency of the Brayton cycle increases as a result of regeneration since the portion of energy of the exhaust gases that is normally rejected to the surroundings is now used to preheat the air entering the combustion chamber. This, in turn, decreases the heat input (thus fuel) requirements for the same net work output. Note, however, that the use of a regenerator is recommended only when the turbine exhaust temperature is higher than the compressor exit temperature. Otherwise, heat will flow in the reverse direction (to the exhaust gases), decreasing the efficiency. This situation is encountered in gas-turbine engines operating at high pressure ratios[1]. The highest temperature occurring within the regenerator is T_4, the temperature of the exhaust gases leaving the turbine and entering the regenerator. Under no conditions can the air be preheated in the regenerator to a temperature above this value. Air normally leaves the regenerator at a lower temperature, T_5. In the limiting (ideal) case, the air exits the regenerator at the inlet temperature of the exhaust gases T_4[1].

Assuming the regenerator to be well insulated and any changes in kinetic and potential energies to be
negligible, the actual and maximum heat transfers from the exhaust gases to the air can be expressed as [1] :

$$q_{regen,act} = h_5 - h_2 \qquad (1)$$

and

$$q_{regen,max} = h_{5'} - h_2 = h_4 - h_2 \qquad (2)$$

Where $q_{regen,act}$ is the actual heat transfers and $q_{regen,max}$ is the maximum heat transfer, the extent to which a regenerator approaches an ideal regenerator is called the effectiveness and is defined as [1] :

$$\epsilon = \frac{q_{regen,act}}{q_{regen,max}} = \frac{h_5 - h_2}{h_4 - h_2} \qquad (3)$$

Where ϵ is the regenerator effectiveness, when the cold-air-standard assumptions are utilized, it reduces to:

$$\epsilon \cong \frac{T_5 - T_2}{T_4 - T_2} \qquad (4)$$

A regenerator with a higher effectiveness obviously saves a greater amount of fuel since it preheats the air to a higher temperature prior to combustion.

However, achieving a higher effectiveness requires the use of a larger regenerator, which carries a higher price tag and causes a larger pressure drop. Therefore, the use of a regenerator with a very high effectiveness cannot be justified economically unless the savings from the fuel costs exceed the additional expenses involved. The effectiveness of most regenerators used in practice is below 0.85. Under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle with regeneration is [1]:

$$\eta_{th,regen}=1-\left(\frac{T_1}{T_3}\right) r_p^{(k-1)/k} \tag{5}$$

where $\eta_{th,regen}$ is the thermal efficiency of regenerative Brayton cycle, T_1 is ambient temperature, T_3 is turbine inlet temperature (also known as TIT), r_p is pressure ratio, and K is the specific heat ratio.[1].

The pressure ration can be expressed as [1]:

$$r_p=\frac{P_2}{P_1} \tag{6}$$

where r_p is the pressure ratio, P_1 is the pressure at the inlet compressor and P_2 is the pressure at the outlet compressor, the net work is:

$$W_{net}=W_{turb,out}-W_{comp,in} \tag{7}$$

Where W_{net} is net work, $W_{turb,out}$ is the work produced by the turbine, and $W_{comp,in}$ is the work consumed by the compressor, hence, the net power can be calculated as:

$$P = \dot{m}_a \times W_{net} \tag{8}$$

Where P is the net power, $\dot{m}_a$ is the air mass flow rate, also the specific fuel consumption can be calculated as:

$$S.F.C.=\frac{3600 \times \dot{m}_f}{Wnet}=\frac{3600}{AFR \times Wnet} \tag{9}$$

Where C.F.C. is specific fuel consumption, $\dot{m}_f$ is the fuel mass flow rate, and AFR is the air fuel ratio.

III. METHODOLOGY

Assuming constant specific heats, the effect of ambient temperature on thermal efficiency, net power, and specific fuel consumption were studied by using computational performance analysis at varies pressure ratio, turbine inlet temperature, and regenerator effectiveness, the range of ambient temperature and the values of other input parameters were used in the presented study is stated in Table 1.

Table 1 The values of the input parameters

Input parameter	**Symbol**	**value**
Ambient temperature	T_1	270k-310k
Ambient pressure	P_1	100 KPa
Pressure ratio	r_p	2-25
turbine inlet temperature	TIT	1200k-1600k
Regenerator effectiveness	ϵ	0.4-0.9
Specific heat ratio for air	K	1.4
Specific heat at constant pressure for air	C_P	1.005 kJ/kg.k
Specific heat at constant volume for air	C_V	0.718 KJ/kg.k

IV. VALIDATION

The variation of the thermal efficiency (η_{th}) versus air (ambient) temperature at regenerative effectiveness equal to 0.75 from Omar et al. study [12] was selected to validate the computational method used in the presented study, the present study was run for the same operating conditions used in Omar et al. study [12]. Fig. 3 shows the comparison between both results, it was found that both results are very similar with acceptable small error (maximum error is 5%).

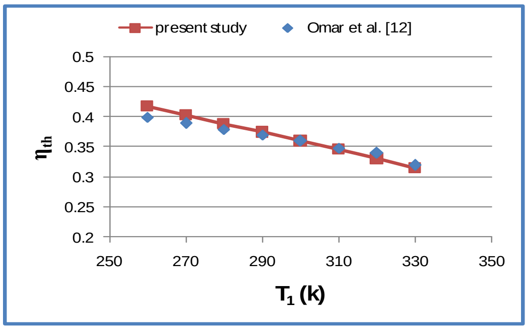

Fig.3 present study results compared with Omar et al. results [12].

V. RESULTS AND DISCUSSION

5.1. Thermal efficiency evaluation

The thermal efficiency performance with pressure ratio is starting to be rapidly increasing at low-pressure ratio r_p=2 to10 then start to decrease after r_p=10, this happens because at high-pressure ratio the compressor exit temperature is higher then turbine exhaust temperature hence, the heat will flow in the reverse direction (to the exhaust gases), decreasing the efficiency (the maximum thermal efficiency value obtained at the selected range is 0.624417 at r_p=10 and T_1=270K.) and in terms of ambient temperature, the thermal efficiency is increasing with ambient temperature decrease (see Fig. 4).

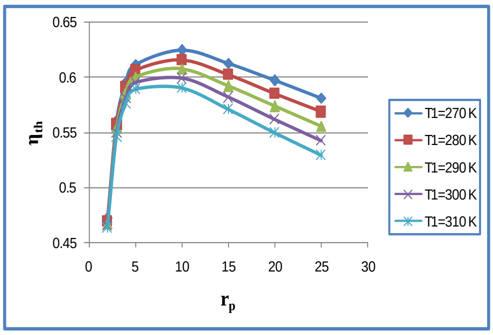

Fig.4 effect of pressure ratio and ambient temperature on thermal efficiency at ϵ=0.8

The relation between thermal efficiency and turbine inlet temperature is semi-linear relation the thermal efficiency increase when turbine inlet temperature increases and regarding the ambient temperature the thermal efficiency increase with ambient temperature decrease (see Fig.5).

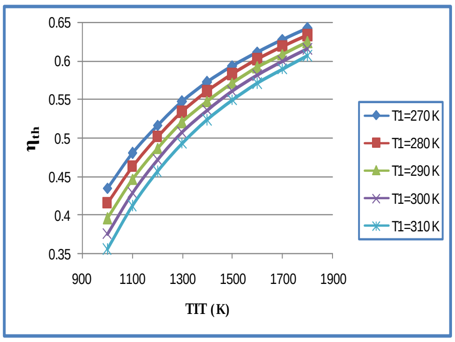

Fig.5 effect of turbine inlet temperature and ambient temperature on thermal efficiency at ϵ=0.8

The relation between thermal efficiency and Regenerator effectiveness is linear relation the thermal efficiency increase when Regenerator effectiveness increases and regarding the ambient temperature the thermal efficiency increase with ambient temperature decrease (see Fig.6).

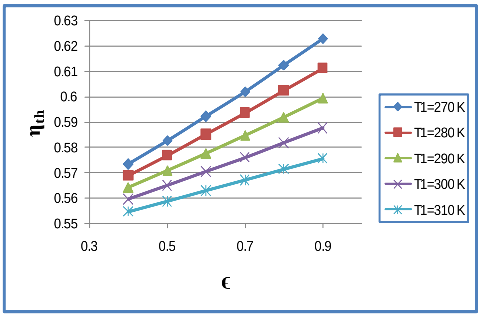

Fig.6 effect of regenerator effectiveness and ambient temperature on thermal efficiency at r_p=15

5.2. Net power evaluation

The net power performance with pressure ratio is starting to be rapidly increasing at low-pressure ratio r_p=2 to15, then start to be semi-constant from r_p=15 to 25 except at T=270 K it's continued slightly increasing from r_p=15 up to r_p=20, while the net power is increasing with ambient temperature decrease (see Fig. 7).

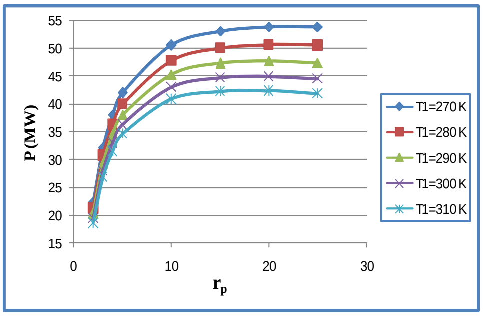

Fig.7 effect of pressure ratio and ambient temperature on net power at ϵ=0.8

The relation between net power and turbine inlet temperature is a linear relation the net power increase when the turbine inlet temperature increases, while the net power increase with ambient temperature decrease (see Fig.8).

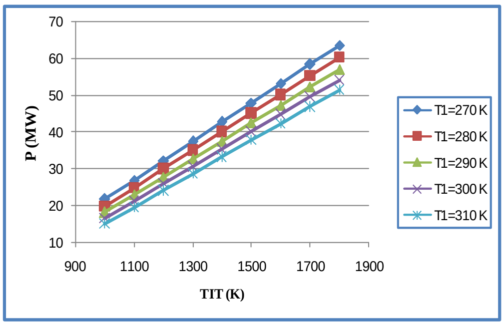

Fig.8 effect of temperature inlet turbine and ambient temperature on net power at ϵ=0.8

5.3. Specific fuel consumption evaluation

The specific fuel consumption performance with pressure ratio is starting to be rapidly decreasing at low-pressure ratio r_p=2 to10, then start to be semi-constant from r_p=10 to 15 then slightly increasing after r_p=15 up to r_p=25, while the specific fuel consumption is increasing with ambient temperature increase (see Fig. 9).

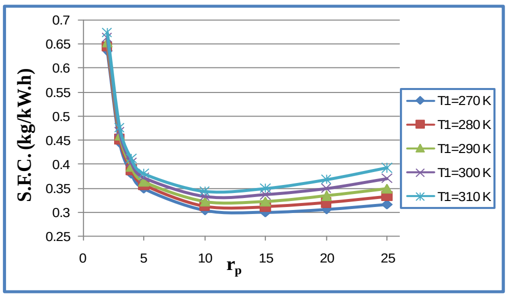

Fig.9 effect of pressure ratio and ambient temperature on specific fuel consumption at ϵ=0.8

VI. CONCLUSIONS

The effect of ambient temperature on regenerative Brayton cycle performance were computationally evaluated in terms of thermal efficiency, net power, and specific fuel consumption at a various range of input values such as pressure ratio, regenerator effectiveness, and turbine inlet temperature, the results show that the thermal efficiency and net power increase with ambient temperature decrease while the specific fuel consumption increase with ambient temperature increase.

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