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Increasing Efficiency of Gas Turbine by Two Methods: Injection of Humid Air and Steam

D. Menbari[1], S. Momeni[2], S. Nasiri[3], P. Alamdari[4], A. A. Alemrajabi[5]

[1] Ph.D. Student, Isfahan University of Technology; d.menbary@me.iut.ac.ir
[2] M.S. Student, Isfahan University of Technology; s.momeni@me.iut.ac.ir
[3] M.S. Student, Isfahan University of Technology; sanaz.nasiri66@gmail.com
[4] M.S. Student, Isfahan University of Technology; p.alamdari@me.iut.ac.ir
[5] Associate Proffesor, Isfahan University of Technology; rajabi@cc.iut.ac.ir

Abstract

In the entire world, the optimization of steam power plant with fossil fuel in order to increase in final generation of power is considered. There are different techniques to increase in efficiency of available power plants with the use of gas turbine. In this research, it is paid to study the Brayton cycle with the injection of compressed and humid air and also steam in order to increase in power and efficiency of gas turbine based on analyse of energy. In this system at first the air is compressed by a compressor and is entered in to the combustion chamber after being humid, which have caused increase in efficiency of this cycles. Then with the injection of steam into combustion chamber, analysis of the thermodynamic first and second law of different parts of cycles is done and the cycles is simulated with EES[1] software and then necessary diagrams are presented. We have paid to comparison of thermal and energy efficiency with simple Brayton cycle and proposed cycles and we have seen the amount of improvement in thermal and energy efficiency in different range of pressure ratios and inlet temperatures.

Keywords: Brayton cycles, compressed air, saturation steam, superheat steam, thermal and exergy efficiency

Introduction

Turbine is one of the systems that have had effective role in generation of electronic energy from many years ago. It has been used for the first time in generation of hydraulic power which is used yet as one of the energy generation in the entire world actively. Since 20th century, utilization of gas turbine has been started and in numerous cases it has been used as main engine for electricity generation especially in power plants.

Construction of gas turbine has been begun from the Second World War and it was quickly developed but it was more considered as a turbojet engine in aviation industry. Later with the development of aerodynamic and material sciences, manufacturer companies succeeded to construct developed turbines. So that nowadays, gas turbines with the pressure ratio of 1:35, efficiency of segments 85 to 90% and entrance temperature of turbine to 1650 k is utilized. In recent years, gas turbines have been developed a lot and it has had different applications. It is used in generation of electronic energy, aviation industry, earthy and marine transportation industry and oil and gas transmission [1]. Main factor in development of gas turbines with high power and efficiency is access to pure natural gas with cheap price. But gas exit with high temperature from the exit of turbine which consequence is decrease in cycle's efficiency, have made experts design compound cycles. Gas turbine power plant may operate either open or close. Open state have been shown in figure 1 that is more general than the other one.

Often an ideal and desired condition in study of power plants of gas turbine power from open type is considered which the same analysis of standard air is. Always two hypotheses are considered in analysis of standard air: 1- work fluid is air which is similar to an ideal gas. 2- Temperature increase which must created by burning is done through heat transmission from an external source. In the analysis of standard air, it is not necessary to investigate complexity of burning process directly, or consider compound's changes through burning [2].

Methods of increasing generation of gas turbines power

Protection of the environment needs to use the adjusted technologies with environment. In energy production field, the use of gas turbine which has less pollution than the other systems has been considered. Also, easiness in installation of gas turbine and plenty of natural gas sources and its relative cheapness have caused increase in demand for it. But the efficiency of gas turbine alone is less than oil-fired of coal steam power plants. This is because of exit of gases obtained from combustion in high temperature from turbine's exhaust. The real efficiency of this system is extremely subjected to temperature of entered air into the compressor. The High temperatures of environment cause the limitation of entered air mass in to the compressor and lead to decrease in turbine exit power. The experiences also have shown that efficiency of gas turbine in cold seasons or even at cooler hours of day will increase. L. Hadic investigated the effects of temperature, pressure, relative humidity and entrance temperature of turbine into power and efficiency of turbine and concluded that temperature of environment have the most effect on turbine's efficiency.

Thermodynamic investigation of this problem by other researchers also showed that thermal efficiency and

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[1] Engineering Equation Solver

turbine exit power will decrease when environment's temperature increase [3]. Theoretical and experimental investigations are carried out by Zhen et al to analyze and predict the humidification process in spray tower and Experimental data were obtained on a pressurized model spray tower at different pressures and water/air ratios [4]. The performance characteristics of two types of regenerative steam injection gas turbine (RSTIG) systems are analyzed, and compared with the performances of the simple gas turbines by Kousuke et al in 2005 [5]. The applied methods of increasing efficiency can be classified in two categories: the cooling the entrance air and the injection of air, steam or water into the turbine.

Injection of compressed air, steam or water in order to increase turbine Power

By this method we can increase the generation of gas turbine power. This act not only increases generation power but also it has desired effect on decrease in air pollution. The different methods of injection water, steam and compressed air are:

1. Use of middle compressor: In this system, water is splashed into the middle floor of the compressor to cool the air and be near to the isotherm compression process. When water is in contact with air with high temperature and pressure, it will be evaporated which cause decrease in temperature.
2. Splash of water or steam into exit of gas turbine's compressor. In this method often splashing water or steam is used to increase the generation of turbine power.
3. Injection of warm and humid compressed air. In this method compressed air is warmed in a separated compressor and then it is humidified 60% and is splashed into the exit of compressor [3].

Governing equations on Segments of Gas Turbine

Brayton cycle is used in a gas turbine cycle which acts as follow: in Brayton cycle, at first the air is compressed adiabatically by centrifuged or axial compressor. Then the air is entered into combustion chamber and then fuel is splashed into the combustion chamber and it is burned at constant pressure. A cycle that includes these three processes is called open cycle which is shown in figure 1.

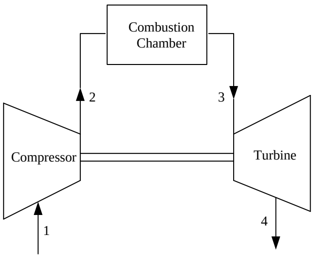

Figure 1: Open Brayton cycle

The real cycle of gas turbine is open cycle because fresh air with low temperature should enter compressor. Analysis of gas turbine cycle is done based on analysis of standard air cycle. In this cycle, air compression and expansion is done at constant entropy and burning reaction is usually replaced with adding heat to the cycle by an external source. Replacement of air in the cycle as the work fluid is a suitable method, because high ratio of air to the fuel in utilization of gas turbines with hydro carbonation fuel is usual.

At Brayton cycle, compression and expansion reaction is done at constant entropy and heat transmission assumed at constant pressure. For these reactions the principle of conservation of energy is as follow [6]:

$$w = \Delta h + \Delta KE \tag{1}$$

Energy balance equation for heat exchanger is:

$$q = \Delta h + \Delta KE \tag{2}$$

If kinetic energy changes are not considered, then we have:

$$w_T = H_3 - H_4 = m\left(h_3 - h_4\right) \tag{3}$$

Energy balance equation and total thermal efficiency and Brayton based cycle thermal efficiency is written as follow:

Energy equation for compressors and pump:

$$w_i = m_{i,inlet}\left(h_{i,inlet} - h_{i,outlet}\right)\eta_i \tag{4}$$

Energy equation for turbines:

$$w_j = m_{j,inlet}\left(h_{j,inlet} - h_{j,outlet}\right)\eta_j \tag{5}$$

Energy equation for heat exchangers:

$$w_c = m_c\left(h_{c,inlet} - h_{c,outlet}\right) = m_h\left(h_{c,inlet} - h_{c,outlet}\right) \tag{6}$$

Total thermal efficiency:

$$\eta_{th,Total} = \frac{\sum w_j - \sum w_t}{m_f LHV} \tag{7}$$

Base thermal efficiency:

$$\eta_{th,Basel} = \frac{w_T - w_C}{m_f LHV} \tag{8}$$

In the presented equations LHV and W alternatively represents low thermal value and work.

Exergy for mass unit is defined as follow:

$$e = \left(h - h_0\right) - T\left(s - s_0\right) \tag{9}$$

External exergy for turbines:

$$E_j = m_{j,inlet}\left(e_{j,inlet} - e_{j,outlet}\right) \tag{10}$$

Used exergy for compressors and pump:

$$E_i = -m_{i,inlet}\left(e_{i,inlet} - e_{i,outlet}\right) \tag{11}$$

Total inlet and outlet exergy is equal to:

$$E_{in} = -m_f\, LHV \tag{12}$$

$$E_{out} = \sum E_j - \sum E_i \tag{13}$$

Total exergy efficiency is equal to:

$$\eta_{ex,Total} = \frac{E_{out}}{E_{in}} \tag{14}$$

Base exergy efficiency:

$$\eta_{ex,Base} = \frac{E_T - E_C}{E_{in}} \tag{15}$$

For determine the proposed cycle’s performance, Brayton cycle with the injection of humid air is considered and for different segments of the cycle, thermodynamic relations at steady state is established.

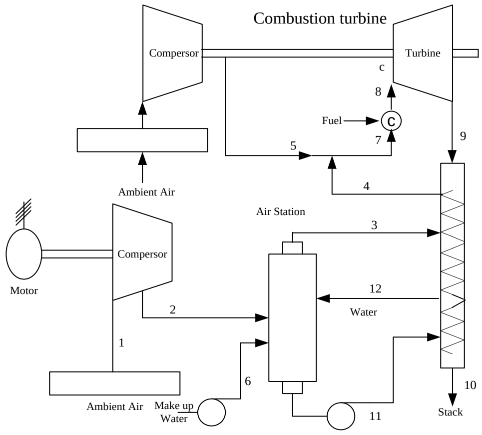

Figure 2: Simplified Brayton cycle with the injection of compressed and humid air

With continuity equation, we write the first thermodynamic law for different segments of the cycle. Exergy and energy's equilibrium equations without consideration the pressure drop in pipe lines, heat exchanger and combustion chamber is valid for every unit of the cycle. Continuity equations and the first law for cycle segments;

Absorbent chamber:

$$\dot{m}_1 h_2 + \dot{m}_{11}\left(h_{12} - h_{11}\right) + \dot{m}_w h_6 = \left(\dot{m}_1 - \dot{m}_w\right) h_3 \tag{16}$$

$$\left(\dot{m}_1 - \dot{m}_w\right) h_4 + \dot{m}_5 h_5 = \dot{m}_7 h_7 \tag{17}$$

For combustion chamber we have:

$$\dot{m}_7\left(h_8 - h_7\right) = \dot{m}_f\, LHV \tag{18}$$

The second proposed cycle is the gas turbine with injection of saturated and superheat steams. The effect of superheat steam on efficiency increasing is more than saturated steam. The steam has a pressure equal to pressure of combustion chamber. With adding steam, fluid mass increases and the act of outlet turbine become more. Since temperature of injected steam is less than maximum temperature of cycle, an excess heat should be spent to raise the temperature of steam to the turbine inlet temperature and this causes decrease the efficiency of cycle, but generally the efficiency is more than simple cycle.

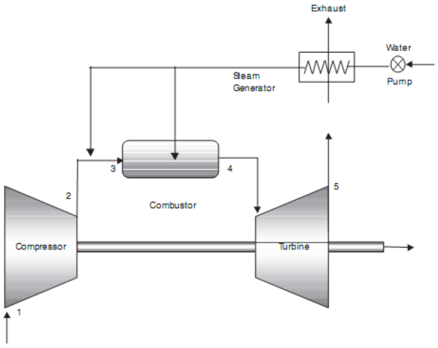

Figure 3: Simplified Brayton cycle form with the injection of steam

For combustion chamber we have:

$$\dot{m}_{steam} h_{steam} + \dot{m}_3 h_3 + \dot{m}_f\, LHV = (\dot{m}_3 + \dot{m}_{steam}) h_4 \tag{19}$$

According to the presented equations at this part and use of EES software we will analyze Brayton cycle with injection of humid air and steam. The presented conclusions include the amount of improvement of proposed cycle thermal and exergy efficiency toward simple Brayton cycle.

Results and Discussion

In this study we investigate Brayton simple cycle and the injection of compressed air and steam with the use of EES [7] software. The assumptions considered for analyzing of proposed thermodynamic system are:

1. Steady state is considered.
2. System segments are well insulated.
3. Energy and exergy equilibrium equations are established for every unit of cycle.

The used data for analyzing considered cycle have been brought in table 1.

Table 1: Data for analyzing considered cycle

0.85	Compressor’s Isentropic Efficiency
0.85	Turbine’s Isentropic Efficiency
50056 (kj/kg)	Heat Value
2.7 (kg/s)	Mass Rate

Results obtained from the data of table 1 for considered cycles have been shown at figure 4 to 7.

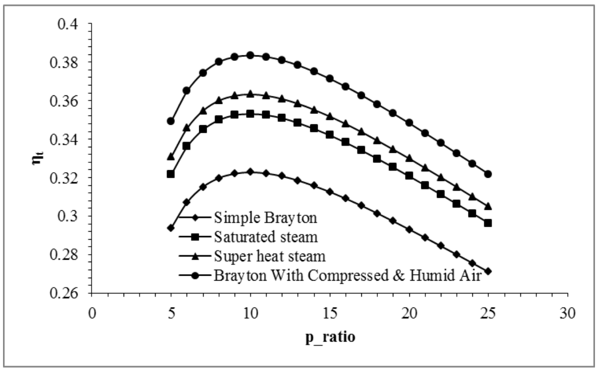

Figure 4: Variation of thermal efficiency with respect to the increasing pressure ratio

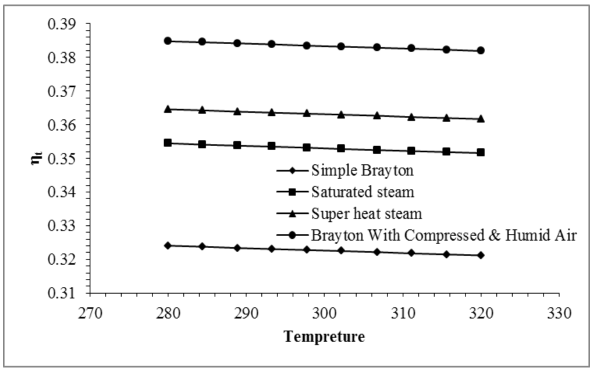

Figure 5: Variation of thermal efficiency with respect to the increasing environment's temperature

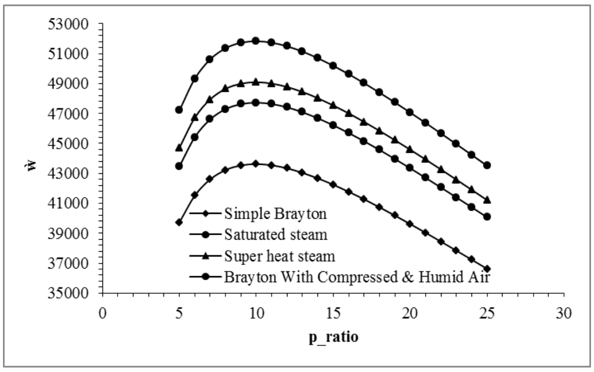

Figure 6: The effect of pressure ratio on power cycles

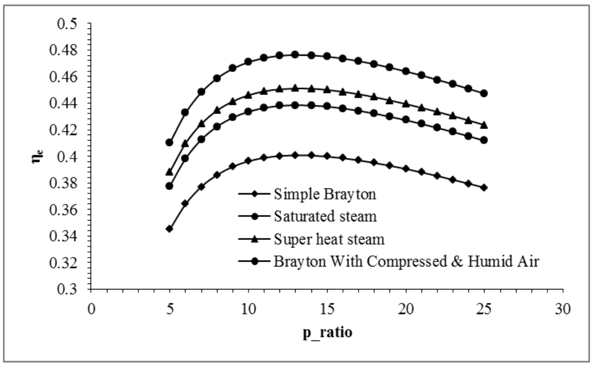

Figure 7: Variation of exergy's efficiency with respect to the increasing environment's temperature

Conclusions

Diagrams 4 to 8 show that thermal efficiency, exergy and pure work in Brayton cycle with the injection of compressed and humid air are higher than simple Brayton cycle in different pressure ratios. The increasing pressure ratio leads to increasing thermal and exergy efficiency and turbine power some extent. It's found that there is one optimum point for cycle performance. At higher pressure ratios, thermal and exergy efficiency increasing is more than low pressure ratios.

The diagrams 3 to 7 show that we can increase thermal efficiency of the cycle about 2.5% and exergy efficiency about 7% by injection of humid and compressed air. With the injection of saturated steam into the combustion chamber, thermal efficiency improves about 7% and also exergy efficiency improves about 14%, also outlet pure work cycle increases about 5%. The other effective parameter is the environment temperature, so that with the reduction in this temperature, compressor's work will decrease and then thermal and exergy efficiency will increase.

List of Symbols

E	Total Exergy
H	Total Enthalpy
s	Entropy
T	Temperature
LHV	Low Heat Value
$\dot{m}_f$	Mass Rate of fuel

Greek symbols

η	Thermal Efficiency
η_e	Exergy Efficiency

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