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Research Article

Performance Analysis of Air Fuel Heating Effects on Cogeneration Cycles

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Abstract

The electrical energy consumption is increasing in our country and in the world. The electrical energy and heat energy are primary energies and has a vital role on industry and our lives. The production of these two energies in different cycles leads to energy loss and low efficiency. With the production of both in the same cycle, the efficiency increases a lot, and the energy losses and emission values decrease a lot. By installing cogeneration system to produce electrical and heat energy, the energy consumption costs can be reduced importantly. The cycle in which the fuel and the air entering into combustion chamber is heated by the heat taken from the exhaust gases at the outlet of the gas turbine is analyzed by using exergy analysis method and, first and second laws of thermodynamics. The heat energy remained in the exhaust gases are used to produce in steam production, after some heat energy is consumed to heat the air and the fuel, in this cycle. The performance analysis of the devices that make up the cycle such as turbine, recuperator compressor, combustion chamber, and heat exchanger and for the whole cycle and were obtained and discussed. Exergy efficiency, exergy losses and other performance parameters of the devices were obtained and discussed.

Keywords: Cogeneration, Exergy, Air fuel heating.

Hava Yakıt Isıtmanın Kojenerasyon Çevrimleri Üzerindeki Etkilerinin Performans Analizi

Öz

Ülkemizde ve dünyada elektrik enerjisi tüketimi giderek artmaktadır. Elektrik enerjisi ve ısı enerjisi birincil enerjilerdir ve endüstride ve hayatımızda hayati bir role sahiptir. Bu iki enerjinin farklı döngülerde üretilmesi, enerji kaybına ve verimin düşmesine neden olur. Her ikisinin de aynı çevrimde üretilmesi ile verim çok artar, enerji kayıpları ve emisyon değerleri çok azalır. Elektrik ve ısı enerjisi üretmek için kojenerasyon sistemi kurularak, enerji tüketim maliyetleri önemli ölçüde azaltılabilir. Gaz türbini çıkışında egzoz gazlarından alınan ısı ile yanma odasına giren yakıtın ve havanın ısıtıldığı çevrim, ekserji analizi yöntemi ve termodinamiğin birinci ve ikinci yasaları kullanılarak analiz edilmiştir. Egzoz gazlarında kalan ısı enerjisi, bu çevrimde havayı ve yakıtı ısıtmak için bir miktar ısı enerjisi tüketildikten sonra buhar üretiminde kullanılır. Türbin, reküperatör kompresör, yanma odası, ısı eşanjörü gibi çevrimi oluşturan cihazların ve tüm çevrim için performans analizleri elde edilmiş ve tartışılmıştır. Cihazların ekserji verimi, ekserji kayıpları ve diğer performans parametreleri elde edilmiş ve tartışılmıştır.

Anahtar Kelimeler: Kojenerasyon, Ekserji, Hava yakıt ısıtma.

1. Introduction

In the conventional system, there is heat generation in two separate systems to produce power and heat. In the cogeneration system, on the other hand, the heat produced with the help of a single heat generation system is first produced with electrical energy with the energy carrier fluid, and the remaining heat energy is used for steam or hot water production. In this case, while the total energy efficiency of the classical (conventional) system is around 58%, the energy efficiency of the cogeneration plant can reach up to 90%. If these two situations are compared, it is seen that there is an opportunity to benefit from the energy of the fuel approximately 30% more in the cogeneration plant. In addition, operating and initial investment costs of the system can be significantly reduced when a cogeneration facility is installed in systems that need heat and electrical energy at the same time. Cogeneration systems; It can be classified as central use plant systems, industrial systems and small systems. However, the characteristics of all three are different and in some applications one can replace the other. Central-use plant systems and industrial systems have been available for many years, and today the main trend, orientation and development is in small systems (ASHRAE, 2000; Karaali and Öztürk, 2015; Peters et al., 2003).

The main engine's characteristics are the gas turbine, like working method, and efficiency affect the properties, the working conditions of the overall cycle. It is possible to classify according to the working methods of this cycles as gas-steam turbine combined cogeneration cycles, gas turbine cogeneration cycles, steam turbine cogeneration cycles, fuel cells and motorized cogeneration cycles. Adding a steam turbine to the cycle for using the exhaust heat coming from the gas turbine the combined (gas-steam) cogeneration systems, can be obtained. If the steam is in the state of low pressure, it is used a process. By adding a second combustion chamber, the combined system can provide very flexible electricity to heat ratio (ASHRAE, 2000; Karaali and Öztürk, 2015; Peters et al., 2003).

In the motorized cogeneration plants, it can be produced steam from the exhaust gases at around 300 – 550 ^{0}C, and overall efficiency about 75–92% can be obtained. For this plant, advantages like low facility costs, high electrical efficiency, short operating and interruption times for maintenance-repair, and low heat rates, can be said. It is possible to benefit from energy at a higher rate by converting the large-scale conventional power plants, which are common in our country, to combined heat-power systems. Karaali and Öztürk (2015) designed the case of converting an existing conventional power plant to a cogeneration system for district heating and examined the thermodynamic and economic feasibility of this alternative situation, and their results were calculated of both energies saving and the environmental effect, and economic feasibility. compared with the current system. With this conversion, it has been seen that the country's resources can be saved with a clean environment and less dependence on natural gas. It has been shown that if the facility established to generate electricity is converted into a cogeneration facility and a very small amount of electricity generation is given up, district heating can be made and its efficiency will increase. The investment costs required for this return within a year and it is seen that the investment is profitable (Karaali and Öztürk, 2015; Bejan et al., 1996; Horlock, 1997).

In fuel cells, electricity is produced as a result of the electrochemical reaction of fuel (Hydrogen or Methane) and oxygen in a fuel cell (around 280 ^{0}C), and heating etc. from low temperature wastes. It is possible to use it as a heat source for processes such as in these systems, the electrical energy production efficiency can be over 75% and the cogeneration efficiency can be over 90%. When these advantages mentioned in such facilities are evaluated, a significant amount of energy savings can be achieved with a more economical energy production. In addition, less environmental pollution is created and the amount of CO_2 released into the atmosphere is at lower levels.

Due to the emergence of more heat and power needs in 1980s, gas turbine cogeneration cycls have become widespread in the world and many studies have been carried out and published by many researchers on their exergy analysis since the early 1980s. Changing heat and electricity needs have increased the interest in gas turbine plants, and the widespread use of natural gas due to its advantages over other fuels, this interest has come to this day. Injection steam in a combustion chamber started in the 1950s in order to reduce the combustion chamber exit temperature and increase the work force obtained, and it continues to be applied today because it reduces NOx and its compounds to a minimum level and improves efficiency (Karaali and Öztürk, 2010; Jaluria, 2008)

2. Material and Method

A gas turbine cogeneration system's main device is the gas turbine. It can be seen in figure 1, air is pressured in a compressor, after that it is burned with the fuel in a combustion chamber. Exhaust gases at high temperatures are produced at the outlet of the combustion chamber give some of its energy in the turbine to produce electricity by the generator. After that, most of its heat energy passes to the water in the HRSG. By that way, electrical energy from the generator and steam or hot water from the HRSG is obtained at the same time.

The steam or hot water are used in drying, heating, or for the process heat needs. Also, the steam or the hot water are used sometimes for district heating, electricity production by using steam turbines, absorption cooling, or other needs. By using and adding some components like steam or water injection, heat exchangers, recuperator, steam turbine added to the main machine, or absorption cooling different systems can be obtained. Also, by using different fluids like CO_2 as the working fluid, different cycles can be obtained.

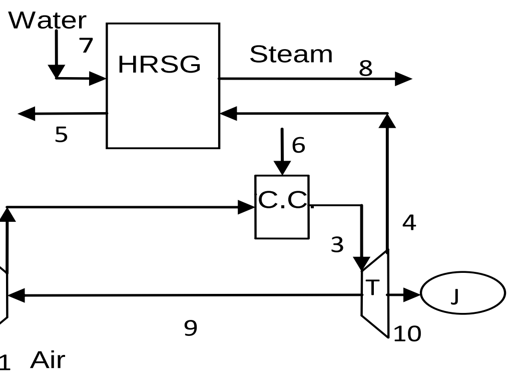

Fig. 1 The diagram of the basic (bsc) cogeneration system.

In Figure 2, air fuel heating (afh) cogeneration plants is shown. In that system, some of the heats are used to heat the air and the fuel, and the other heats are used to produce steam. Cogeneration plants consist some different components and temperature, chemical composition and pressure changes happen in those components. Also, in the combustion chamber a chemical reaction are obtained.

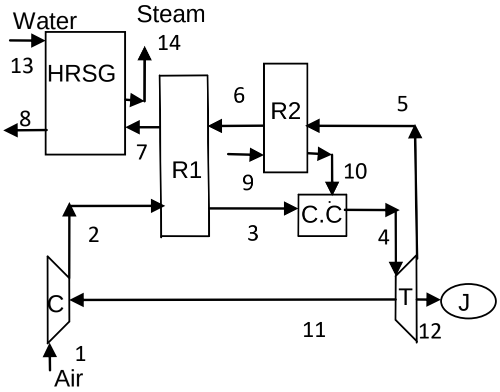

Fig. 2 The diagram of the air fuel heating (afh) cogeneration system.

Assumptions made in the calculations and in the analysis of the system in this study are as follows (Bejan et al., 1996). The system works in the continuous regime, the laws of ideal gas mixture are applied to exhaust and air. The fuel is Methane, and that taken as ideal gas. Also, combustion is complete, there are no NOx formation. There is no heat loss except from the combustion chamber and are 2% upper calorific value of the fuel. An open system that the properties of the matter is uniformly distributed in each area of the control surface where there is a mass exchange, and the heat and the work exchanges is not change over time which are called continuous flow continuous open. For open system and steady state, the first law of thermodynamics,

$$\dot{Q}_{KH} - \dot{W}_{KH} + \sum_g \dot{m}_g \left(h_g + \frac{{V_g}^2}{2} + gz_g\right) - \sum_c \dot{m}_c \left(h_c + \frac{{V_c}^2}{2} + gz_c\right) = 0 \tag{1}$$

In steady state, the law of conservation of mass is,

$$\sum \dot{m}_g = \sum \dot{m}_ç \tag{2}$$

In combustion the chemical energies are converted into thermal energy. For this study it is assumed that the combustion reaction takes place ideally and completely. It is also assumed that the natural gas is methane gas to simplify the calculations. the following chemical reaction is taken as a basis,

$$\bar{\lambda}CH_4 + (0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O \rightarrow (1+\bar{\lambda})(X_{N2}N_2 + X_{O2}O_2 + X_{CO2}CO_2 + X_{H2O}H_2O) \tag{3}$$

The minimum mass of air required to complete theoretical combustion is called the stoichiometric amount of air. However, for complete combustion more air than the theoretical amount of air is always used. The excess air coefficient is the ratio of the actual amount of air to the theoretical amount of air (Bejan et al., 1996; Horlock, 1997).

In table 1, energy, entropy and mass equations of the devices of the air fuel heating (afh) system are given.

In table 2, exergy efficiency, and exergy equations of the devices of the air fuel heating (afh) system are given.

Table 1. Energy, entropy and mass equations of the devices of the air fuel heating (afh) system (Bejan et al., 1996; Moran et al., 2000; Horlock, 1997; Peters et al., 2003).

Component	Mass Equation	Energy Equation	Entropy Equation
Compressor	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1h_1 + \dot{W}_C = \dot{m}_2h_2$	$\dot{m}_1s_1 - \dot{m}_1s_2 + \dot{S}_{gen,C} = 0$
Recuperator1	$\dot{m}_2 = \dot{m}_3$ $\dot{m}_6 = \dot{m}_7$	$\dot{m}_2h_2 + \dot{m}_6h_6 = \dot{m}_3h_3 + \dot{m}_7h_7$	$\dot{m}_2s_2 + \dot{m}_6s_6 - \dot{m}_3s_3 - \dot{m}_7s_7 + \dot{S}_{gen,R1} = 0$
Recuperator2	$\dot{m}_5 = \dot{m}_6$ $\dot{m}_9 = \dot{m}_{10}$	$\dot{m}_5h_5 + \dot{m}_9h_9 = \dot{m}_6h_6 + \dot{m}_{10}h_{10}$	$\dot{m}_5s_5 + \dot{m}_9s_9 - \dot{m}_6s_6 - \dot{m}_{10}s_{10} + \dot{S}_{gen,R2} = 0$
Combustion Chamber	$\dot{m}_3 + \dot{m}_{10} = \dot{m}_4$	$\dot{m}_3h_3 + \dot{m}_{10}h_{10} = \dot{m}_4h_4 + 0.02\dot{m}_{10}LHV$	$\dot{m}_3s_3 + \dot{m}_{10}s_{10} - \dot{m}_4s_4 + \dot{S}_{gen,CC} = 0$
Turbine	$\dot{m}_4 = \dot{m}_5$	$\dot{m}_4h_4 = \dot{W}_T + \dot{W}_C + \dot{m}_5h_5$	$\dot{m}_4s_4 - \dot{m}_5s_5 + \dot{S}_{gen,T} = 0$
HRSG	$\dot{m}_7 = \dot{m}_8$ $\dot{m}_{13} = \dot{m}_{14}$	$\dot{m}_7h_7 + \dot{m}_{13}h_{13} = \dot{m}_8h_8 + \dot{m}_{14}h_{14}$	$\dot{m}_7s_7 + \dot{m}_{13}s_{13} - \dot{m}_8s_8 - \dot{m}_{14}s_{14} + \dot{S}_{gen,HRSG} = 0$
Overall Cycle	$\bar{h}_i = f(T_i)$ $\bar{s}_i = f(T_i, P_i)$ $\dot{m}_{air}h_{air} + \dot{m}_{fuel}LHV_{CH4} - \dot{Q}_{Loss,CC} - \dot{m}_{eg.,out}h_{eg.,out} - \dot{W}_T - \dot{m}_{steam}(h_{water,in} - h_{steam,out}) = 0$ $\dot{Q}_{Loss,CC} = 0.02\dot{m}_{fuel}LHV_{CH4}$		

Exergy or availability are theoretical maximum value of the useful work. Which can be obtained if equilibrium with the environment is achieved at the end of a reversible process. It has two components, chemical and physical. The perfect gas mixtures physical exergy can be written in molar terms for mixed substances,

$$e_{phy} = (\bar{h} - \bar{h}_0)_{mix} - T_0.(s - s_0)_{mix} = \sum_i x_i \left[\int_{T_0}^{T} \bar{c}_{p0i}(T)dT - T_0.\left(\int_{T_0}^{T} \frac{\bar{c}_{p0i}(T)}{T}dT - \bar{R}\,ln\frac{P_i}{P_0}\right)\right] \tag{4}$$

The chemical exergies are maximum useful works which can be obtained when a substance in the reference state (T_0, P_0) becomes thermodynamic equilibrium in terms of chemical composition with its surroundings (Bejan et al., 1996; Horlock, 1997).

The chemical exergy of the gas mixtures is,

$$\bar{e}_{chem,mix} = \sum_i x_i.\bar{e}_{chem,i} + \bar{R}.T_0.\sum_i x_i.ln\,x_i \tag{5}$$

Thus, the total exergy of a flow or control mass can be written as

$$\overline{E} = \overline{E}_{phy} + \overline{E}_{chem} \quad (6)$$

Table 2. Exergy equations, and exergy efficiency equations of the devices of the air fuel heating (afh) cycle (Bejan et al., 1996; Moran et al., 2000; Horlock, 1997; Peters et al., 2003).

Component	Exergy Equation	Exergy Efficiency
Compressor	$\dot{E}_{D,C} = \dot{E}_1 + \dot{W}_C - \dot{E}_2$	$\eta_{ex,C} = \frac{\dot{E}_{out,C} - \dot{E}_{in,C}}{\dot{W}_C}$
Recuperator1	$\dot{E}_{D,R1} = \dot{E}_2 + \dot{E}_6 - \dot{E}_3 - \dot{E}_7$	$\eta_{ex,R1} = \frac{\dot{E}_{out,air,R1} - \dot{E}_{in,air,R1}}{\dot{E}_{out,exhaust,R1} - \dot{E}_{in,exhaust,}}$
Recuperator2	$\dot{E}_{D,R2} = \dot{E}_5 + \dot{E}_9 - \dot{E}_6 - \dot{E}_{10}$	$\eta_{ex,R2} = \frac{\dot{E}_{out,air,R2} - \dot{E}_{in,air,R2}}{\dot{E}_{out,exhaust,R2} - \dot{E}_{in,exhaust,}}$
Combustion Chamber	$\dot{E}_{D,CC} = \dot{E}_3 + \dot{E}_{10} - \dot{E}_4$	$\eta_{ex,CC} = \frac{\dot{E}_{out,CC}}{\dot{E}_{in,CC} + \dot{E}_{fuel}}$
Turbine	$\dot{E}_{D,T} = \dot{E}_4 - \dot{E}_5 - \dot{W}_C - \dot{W}_T$	$\eta_{ex,T} = \frac{\dot{W}_{net,T} + \dot{W}_C}{\dot{E}_{in,T} - \dot{E}_{out,T}}$
HRSG	$\dot{E}_{D,HRSG} = \dot{E}_7 - \dot{E}_8 + \dot{E}_{13} - \dot{E}_{14}$	$\eta_{ex,HRSG} = \frac{\dot{E}_{steam,HRSG} - \dot{E}_{water,HR}}{\dot{E}_{in,exhaust,HRSG} - \dot{E}_{out,exhau}}$
Overall cycle	Exergy efficiency	$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch}$ $\dot{E}_{ph} = \dot{m}(h - h_0 - T_0(s - s_0))$ $\dot{E}_{ch} = \frac{\dot{m}}{M}\left\{\sum x_k \bar{e}_k^{ch} + \bar{R}T_0 \sum x_k \ln x_k\right\}$ $\eta_{ex} = \frac{\dot{W}_{net,T} + (\dot{E}_{steam,HRSG} - \dot{E}_{w}}{\dot{E}_{fuel}}$

Exergy equation for open systems which input and output mass quantities are equal to each other is,

$$\sum_i \dot{m}_i h_i - \sum_i T_0 S_i - \sum_j \dot{m}_j h_j + \sum_j T_0 S_j + \sum \dot{Q}_k - \sum \dot{Q}_k \frac{T_0}{T_k} - \dot{W} = \dot{E}_{loss} \quad (7)$$

3. Results and Discussion

In figure 3, variation of exergy efficiency and electrical efficiency of the air fuel heating (afh) and basic (bsc) cogeneration systems with compressing ratio are given. As can be seen that the air fuel heating (afh) cycle has higher efficiency than the basic (bsc) one approximately 9%. Also, the air fuel heating (afh) cycle has higher electrical efficiency than the basic (bsc) one approximately 21%.

In figure 4, variation of exergy efficiency of the air fuel heating (afh) cogeneration plant with excess air rates for different compression ratio are given. It is concluded those, increasing excess air rates affect increases in the exergy efficiency of the air fuel heating (afh) about 25%. Also, increasing the compression ratio have an effect on increasing the exergy efficiency of the air fuel heating (afh) about 13%.

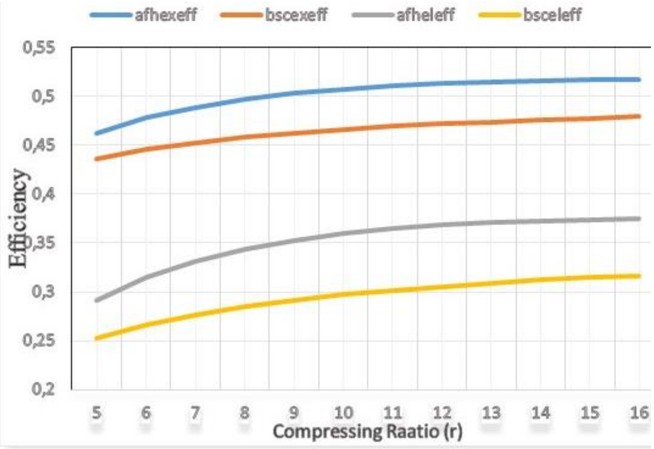

Fig. 3 Variation of exergy efficiency and electrical efficiency of the air fuel heating (afh) and basic (bsc) cogeneration systems with compressing ratio.

In figure 5, variation of efficiencies of the compressor, the combustion chamber, the turbine, and the HRSG of the air fuel heating (afh) system with compression ratio are given. An increase in the compression ratio results an increase in the efficiency of the compressor about 1.7%, the recuperator about 17%, the combustion chamber about 2%, and the (heat exchanger) HRSG about 4.4% for the afh cycle. But, increasing the compression ratio decreases the efficiency of the turbine about 3.6%.

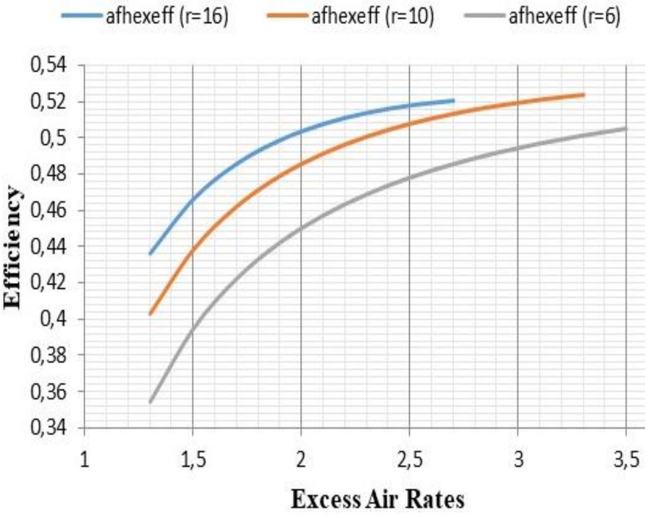

Fig. 4 Variation of exergy efficiency of the air fuel heating (afh) cogeneration system with excess air rates for different compression ratio.

In figure 6, variation of exergy efficiency of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures are given. As concluded that, increasing the excess air rates of the afh cogeneration system increases the exergy efficiency about 30 %. Decreasing the excess air ambient temperatures increases the exergy efficiency about 1%.

In figure 7, variation of electrical efficiency of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures. That is seen, the electrical efficiency of the afh cogeneration plant increases with the excess air rates about 85%. Also, decreasing the excess air ambient temperatures from 308 K to 288K increases the electrical efficiency about 7%.

In figure 8, variation of efficiency of the compressor of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures are given. It is concluded this, increasing the excess air rates do not have a real effect on the efficiency of the compressor. However, an increasing in the inlet air temperature cause an increase in the efficiency of the compressor. But decreases the overall cycle exergy efficiency. The reason is, an increase in inlet air temperature cause an increase in compressor work which decreases the turbine work and electricity obtained.

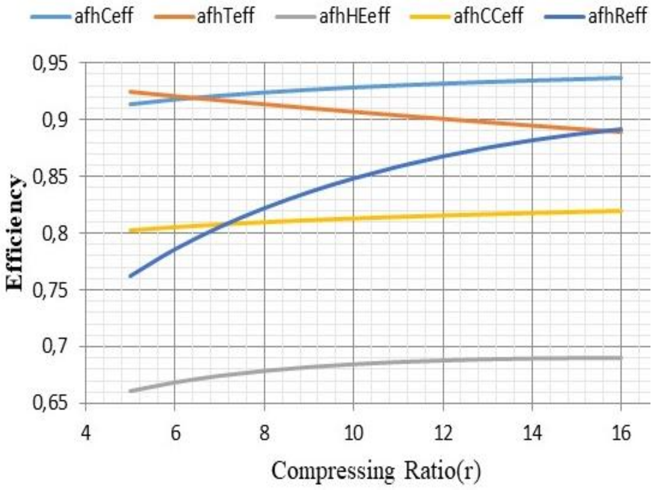

Fig. 5 Variation of efficiencies of the compressor, the turbine, the combustion chamber and the heat recovery steam generator of the air fuel heating (afh) system with compression ratio

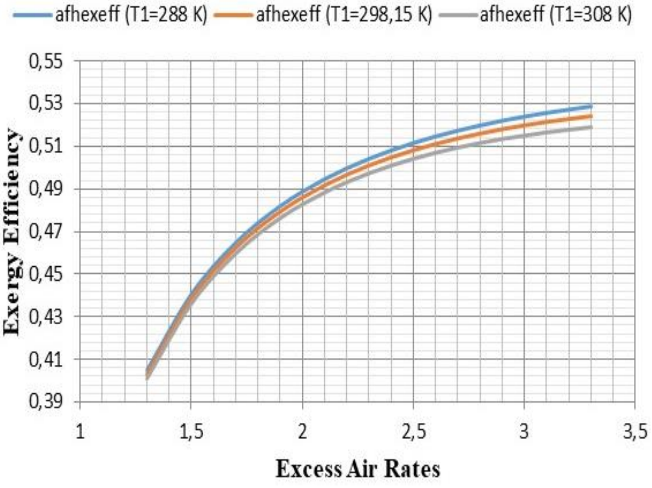

Fig. 6 Variation of exergy efficiency of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures.

In figure 9, variation of efficiency of the turbine of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures are given. It is concluded those, an increase in excess air rates affects an increase in the efficiency of turbine about 12%. Also, decreasing the excess air ambient temperatures from 308 K to 288K increases the turbine efficiency about 0.7%.

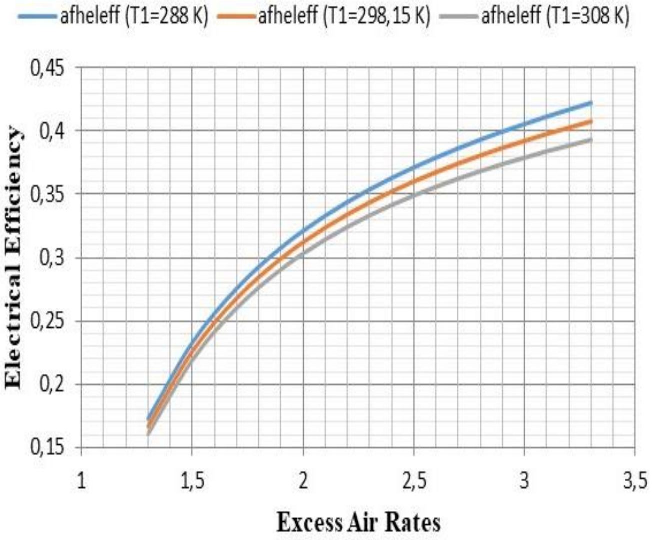

Fig. 7 Variation of electrical efficiency of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures.

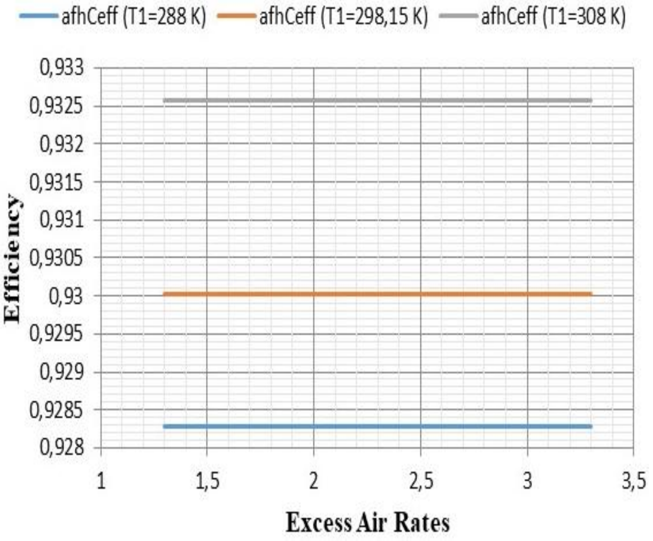

Fig. 8 Variation of efficiency of the compressor of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures.

In figure 10, variation of efficiency of heat exchanger of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures are given. That is concluded these, an increasing in excess air rates cause an increase on efficiency of heat exchanger of air fuel heating (afh) cogeneration system about 36%. Also, decreasing the excess air ambient temperatures from 308 K to 288K increases the heat exchanger efficiency about 3%.

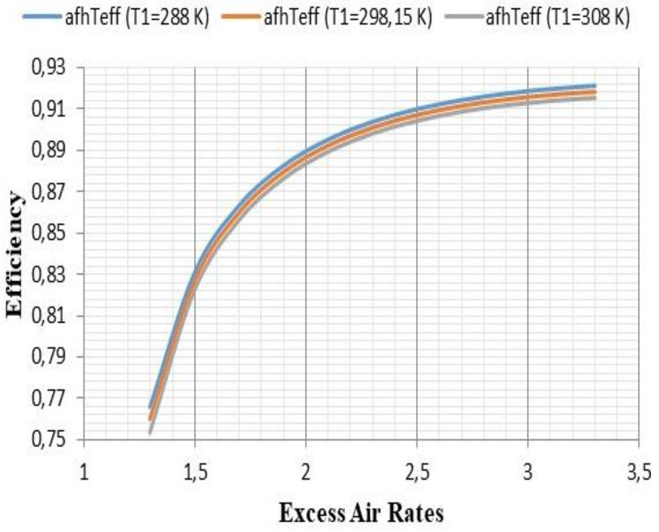

Fig. 9 Variation of efficiency of the turbine of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures.

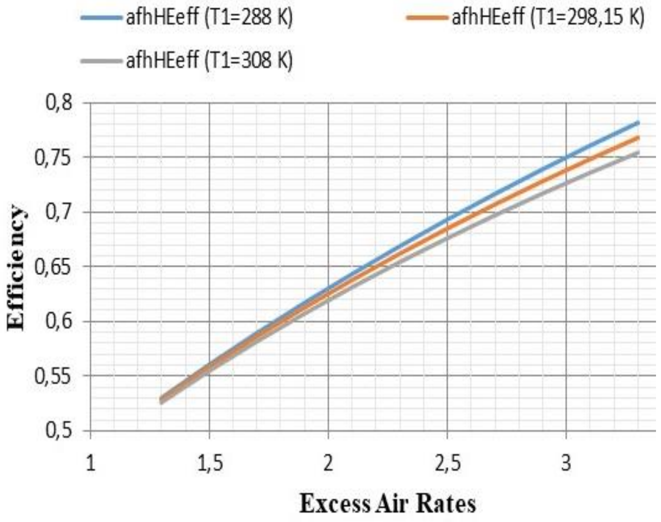

Fig. 10 Variation of efficiency of the heat exchanger of the air fuel heating (afh) cogeneration system with excess air rates for different ambient temperatures.

4. Conclusions and Recommendations

The results showed that using air fuel heating (afh) system in a basic cycle makes better than the basic one in electrical efficiency. Also, the exergy efficiency of the afh plant is higher than the bsc plant. The afh cogeneration system can be used when the electrical demand increases for production more electricity or for more efficiency. The performance like exergy efficiency, electrical efficiency and devices efficiencies are depending on excess air rates, compression ratio and atmospheric temperature, importantly. For every device of the air fuel heating (afh) and basic (bsc) cogeneration system, the energy and the exergy analyses are done. The results of the calculations are given in results section. The performance of the afh cogeneration plant is depending on compression ratio, excess air rates and atmospheric temperature. Less atmospheric temperature, more excess air rates and higher compression ratio can increase the exergy efficiency and electrical efficiency. Excess air rates and compression ratio are very effective on the exergy and electric efficiencies so that these two factors should be optimized. However, excess air rates are very effective on the efficiencies and for 2.3 value of the excess air rates gives the optimum. To obtain all optimum working conditions, a thermodynamic and thermoeconomic optimization must be studied. Also, for further studies in optimizations of the cogeneration systems can found in the literature (Jaluria, 2008; Karaali and Ozturk, 2015; Karaali and Ozturk, 2017; Tozlu, 2021).

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