

Exergetic analyses of air-fuel preheated cogeneration plants in food production

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Abstract. Lower emissions and better performances in food production also affect the cost, the environmental effects, and the quality of the products of the agriculture and food industry. The aim of this study is to investigate and to analyze the exergetic performance of the production of heat exergy and power, to reuse waste heat and to give optimum reaction and to adapt to changing demands of the food production process and agriculture. Because of those reasons, an air fuel preheated (recuperative) cogeneration plant is taken to analyze the exergetic performance and working conditions by using exergy analysis and 1st and 2nd laws of thermodynamics. Energy and exergy efficiencies, combustion chamber and gas-turbine outlet temperatures, electric-heat exergy rates, specific works, and total electric and heat energies and exergies are calculated by taking various environmental temperatures and various excess air coefficient. Effects of the environmental temperatures and the excess air coefficient on the exergetic performance of the recuperative cogeneration plants were calculated, obtained, and discussed. For the best exergetic performance and working conditions, some recommendations were done for agriculture and for the food production process. In that study, it is found that, the recuperative cogeneration plants can obtain and give the best solutions and can adapt to changing demands of heat and electric rates. Also, it was found that, lower ambient temperatures give better electric efficiency, but lower heat exergy and electric rates. However, higher excess air coefficient increases the performance of the recuperative (air fuel preheated) cogeneration plants.

1 Introduction

Lower emissions and better performances in food production also affect the cost, the environmental effects, and the quality of the products of the agriculture and food industry. The aim of this study is to investigate and to analyse the exergetic performance of the production of heat exergy and power, to reuse waste heat and to give optimum reaction and to adapt to changing demands of the food production process and agriculture. Because of those reasons, an air fuel preheated (recuperative) cogeneration plant is taken to analyse the exergetic performance and working conditions by using exergy analysis and 1st and 2nd laws of thermodynamics.

Karaali et al., [1, 2, 3] in their articles have studied the performance, exergetic, parametric analyses and thermoeconomic optimization of an air fuel preheated (recuperative) cogeneration plants. They found that the air fuel preheated (recuperative) cogeneration plants have better performances exergetic and electrical efficiencies than the simple, air heated, and absorption cooled inlet air cogeneration plants.

Keven [4] in her article have investigated performance analyses of three different cogeneration plants which were called air heating, basic, and air-fuel heating cogeneration plants.

In that study the cogeneration system taken from literature (reference [5]) and to this system a fuel preheater was added to obtain a new system. Energy and exergy efficiencies, combustion chamber and gas-turbine outlet temperatures, electric-heat exergy rates, specific works, and total electric and heat energies and exergies are calculated by taking various environmental temperatures and various excess air coefficient of this new system. The effects of the environmental temperatures and the excess air coefficient on the exergetic performance of the recuperative cogeneration plants were calculated, obtained, and discussed.

2 Materials and methods

A cogeneration system obtains some devices in which the main most important device is gas-turbine. Other devices are combustion chamber, compressor, heat recovery steam generator, fuel recuperator and air recuperator. The assumptions made in the analysis of the cycle can be found in reference [5]. Natural gas are taken as methane. The heat loss is taken as 2% of the fuel's UHV at the combustion process at the combustion chamber. As can be seen in Figure 1, air is taken into the compressor to be compressed. After that, it is heated by transferring the exhaust heat energy by using a recuperator. The heated air and fuel are sent to the combustion. After the combustion chamber, some of the

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exhaust gases energy is converted to mechanical energy in the gas-turbine. Hot and low pressured exhaust gases heat the fuel and the air in the recuperators. With those hot gases hot water or steam are obtained in a heat recovery steam generator (HRSG).

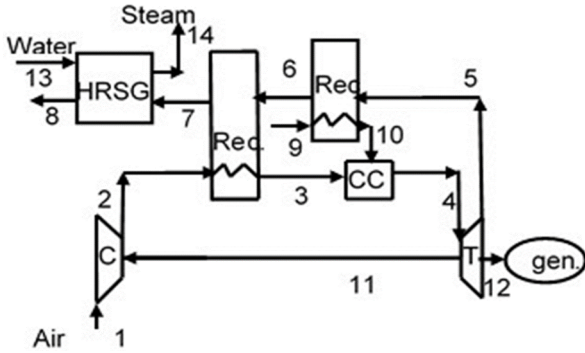


Fig. 1. Schema of the air fuel preheated (recuperative) cogeneration plant.

Table 1. The air fuel preheated (recuperative) cogeneration plant's energy, entropy, and mass equations [2, 5, 6].

DEVICE	Mass Equation	Energy Equation	Entropy Equation
Compressor	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1 h_1 + \dot{W}_C = \dot{m}_2 h_2$	$\dot{m}_1 s_1 - \dot{m}_2 s_2 + \dot{S}_C = 0$
Recuperator1	$\dot{m}_2 = \dot{m}_3$ $\dot{m}_6 = \dot{m}_7$	$\dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3 + \dot{m}_7 h_7$ $\dot{m}_5 h_5 + \dot{m}_9 h_9 = \dot{m}_6 h_6 + \dot{m}_{10} h_{10}$	$\dot{m}_2 s_2 + \dot{m}_6 s_6 - \dot{m}_3 s_3 - \dot{m}_7 s_7 + \dot{S}_{R1} = 0$ $\dot{m}_5 s_5 + \dot{m}_9 s_9 - \dot{m}_6 s_6 - \dot{m}_{10} s_{10} + \dot{S}_{R2} = 0$
Recuperator2	$\dot{m}_5 = \dot{m}_6$ $\dot{m}_9 = \dot{m}_{10}$		
Combustion Chamber	$\dot{m}_3 + \dot{m}_{10} = \dot{m}_4$	$\dot{m}_3 h_3 + \dot{m}_{10} h_{10} = \dot{m}_4 h_4 + 0.02 \dot{m}_{10} LHV$	$\dot{m}_3 s_3 + \dot{m}_{10} s_{10} - \dot{m}_4 s_4 + \dot{S}_{CC} = 0$
Turbine	$\dot{m}_4 = \dot{m}_5$	$\dot{m}_4 h_4 = \dot{W}_T + \dot{W}_K + \dot{m}_5 h_5$	$\dot{m}_4 s_4 - \dot{m}_5 s_5 + \dot{S}_{T,T} = 0$
HRSG	$\dot{m}_7 = \dot{m}_8$ $\dot{m}_{13} = \dot{m}_{14}$	$\dot{m}_7 h_7 + \dot{m}_{13} h_{13} = \dot{m}_8 h_8 + \dot{m}_{14} h_{14}$	$\dot{m}_7 s_7 + \dot{m}_{13} s_{13} - \dot{m}_8 s_8 - \dot{m}_{14} s_{14} + \dot{S}_{HRSG} = 0$
All Cycle	$\dot{h}_i = f(T_i)$ $\dot{s}_i = f(T_i, P_i)$ $\dot{m}_{air} h_{air} + \dot{m}_{fuel} LHV_{CH_4} - \dot{Q}_{Loss,CC} - \dot{m}_{eg,out} h_{eg,out} - \dot{W}_T - \dot{m}_{steam} (h_{water,in} - h_{steam,out}) = 0$ $\dot{Q}_{Loss,CC} = 0.02 \dot{m}_{fuel} LHV_{CH_4}$		

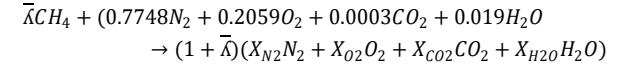
Table 2. The air fuel preheated (recuperative) cogeneration plant's exergy, and exergy efficiencies equations [2, 5, 6].

DEVICE	Exergy Equation	Exergy Efficiency Equation
Compressor	$\dot{E}_{L,C} = \dot{E}_1 + \dot{W}_C - \dot{E}_2$	$\eta_{ex,C} = \frac{\dot{E}_{L,C}}{\dot{W}_C}$
Recuperator1	$\dot{E}_{L,R1} = \dot{E}_2 + \dot{E}_6 - \dot{E}_3 - \dot{E}_7$	$\eta_{ex,R1} = \frac{\dot{E}_{L,R1}}{\dot{E}_{air,R1} - \dot{E}_{air,R1}}$
Recuperator2	$\dot{E}_{L,R2} = \dot{E}_5 + \dot{E}_9 - \dot{E}_6 - \dot{E}_{10}$	$\eta_{ex,R2} = \frac{\dot{E}_{L,R2}}{\dot{E}_{air,R2} - \dot{E}_{air,R2}}$
Combustion Chamber	$\dot{E}_{L,CC} = \dot{E}_3 + \dot{E}_{10} - \dot{E}_4$	$\eta_{ex,CC} = \frac{\dot{E}_{L,CC}}{\dot{E}_{L,CC} + \dot{E}_{fuel}}$
Turbine	$\dot{E}_{L,T} = \dot{E}_4 - \dot{E}_5 - \dot{W}_C - \dot{W}_T$	$\eta_{ex,T} = \frac{\dot{W}_{net,T} + \dot{W}_C}{\dot{E}_{L,T} - \dot{E}_{0,T}}$
HRSG	$\dot{E}_{L,HRSG} = \dot{E}_7 - \dot{E}_8 + \dot{E}_{13} - \dot{E}_{14}$	$\eta_{ex,HRSG} = \frac{\dot{E}_{steam,HRSG} - \dot{E}_{water,HRSG}}{\dot{E}_{L,HRSG} - \dot{E}_{0,HRSG}}$
All Cycle	$\dot{E} = \dot{E}_{phys} + \dot{E}_{che}$ $\dot{E}_{che} = \frac{\dot{m}}{N} \left(\sum x_k \theta_k^{che} + R T_0 \sum x_k \ln x_k \right)$	$\eta_{ex} = \frac{\dot{W}_{net,T} + (\dot{E}_{steam,HRSG} - \dot{E}_{water,HRSG})}{\dot{E}_{fuel}}$

In Table 1, the air fuel preheated (recuperative) cogeneration plant's energy, entropy, and mass equations are shown. In Table 2, the air fuel preheated (recuperative) cogeneration plant's exergy, and exergy efficiencies equations are given.

In the calculations, analyses and in our FORTRAN computer program the equations in Table 1 and Table 2

are used. The combustion reactions in the combustion chamber were taken as;



In this study, the normal conditions are $P_0 = 101.30$ kPa and $T_0 = 25^\circ C$. The air mass flow of the compressor is $\dot{m}_{air} = 91.30$ kg/s, and the flow of the fuel mass is $\dot{m}_{fuel} = 1.640$ kg/s. And the isentropic efficiency of the gas-turbine and the compressor are $\eta_{izC} = \eta_{izT} = 0.86$, the recuperator's outlet temperature is $T_{recout} = 850.0$ K, steam-hot water obtained temperature is $T_{steam} = 485.6$ K, and the HRSG outlet temperatures is $T_{exh} = 426.0$ K [5].

3 Results and discussion

In Fig. 2, combustion chamber outlet temperatures as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are shown. For this cycle the ambient temperatures are not effective on the outlet temperatures of the combustion chamber. Because of the recuperators heats the air and the fuel to the 850 K temperature the inlet temperatures of the combustion chamber are constant. However, excess air coefficient are very effective on the outlet temperatures since the air fuel ratios are changed. Increasing excess air coefficient from 1.3 to 3.3 decreases the outlet temperatures of the combustion chamber about % 36.

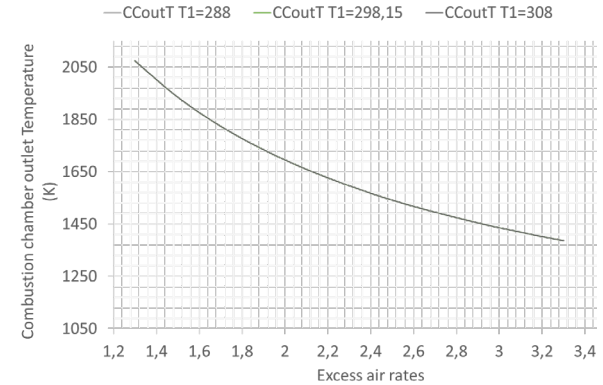


Fig. 2. Effects of excess air coefficient on combustion chamber outlet temperatures for the recuperative cogeneration plant in various ambient temperatures.

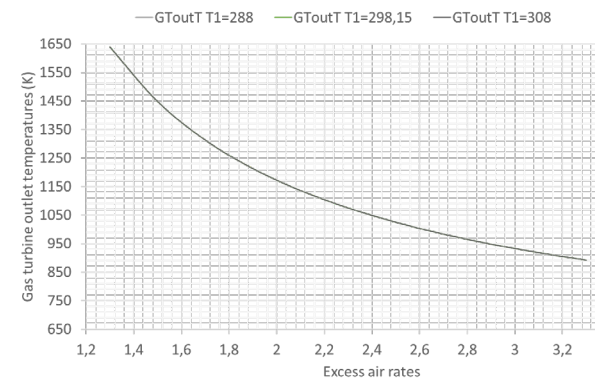


Fig. 3. Effects of excess air coefficient on gas-turbine outlet temperatures for the recuperative cogeneration plant in various ambient temperatures.

In Fig. 3, gas-turbine outlet temperatures as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are obtained. The ambient temperatures are not effective on the outlet temperatures of the gas-turbine. The reason is the outlet temperatures of the combustion chamber are not depended to ambient temperatures. However, excess air coefficient are effective on the outlet temperatures since the air fuel ratios are changed. Increasing excess air coefficient from 1.3 to 3.3 decreases the outlet temperatures of the combustion chamber about % 45.

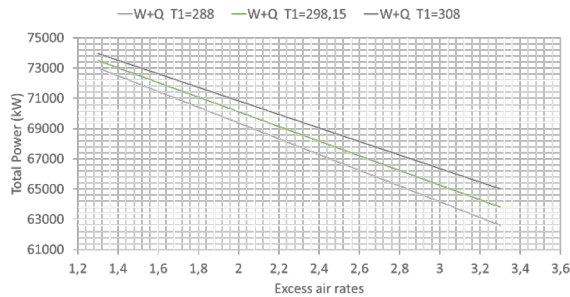


Fig. 4. Effects of excess air coefficient on total power for the recuperative cogeneration plant in various ambient temperatures.

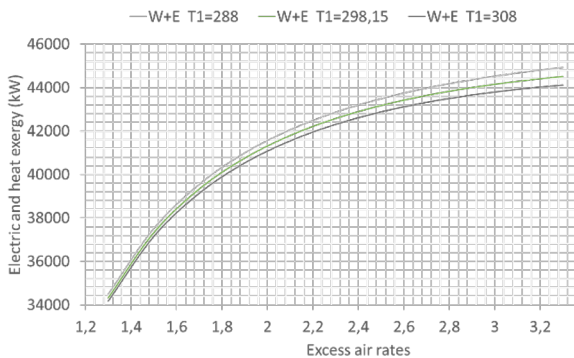


Fig. 5. Electric and heat exergy as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures.

In Fig. 4, total power as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are obtained. Increase in ambient temperatures increases the total power about % 2.6-4. However, increasing excess air coefficient from 1.3 to 3.3 decreases the total power about % 12.

In Fig. 5, electric and heat exergy as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are given. Increase in ambient temperatures decreases the electric and heat exergy about % 0.2-2. However, increasing excess air coefficient from 1.3 to 3.3 increases the electric and heat exergy about % 29.

In Fig. 6, energy efficiency as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are given. Increase in ambient temperatures increases the energy efficiency about % 0.2-2. However, increasing excess air coefficient from 1.3 to 3.3 decreases the energy efficiency about % 14.

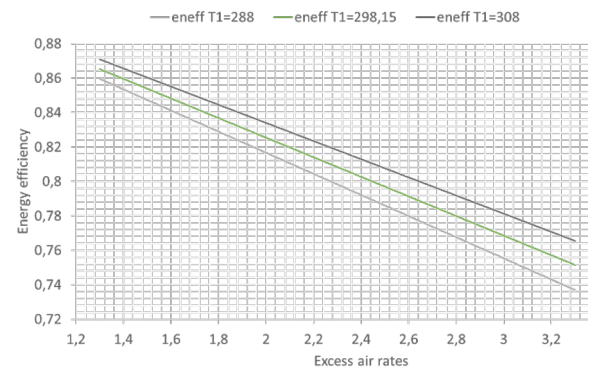


Fig. 6. Effects of excess air coefficient on energy efficiency for the recuperative cogeneration plant in various ambient temperatures.

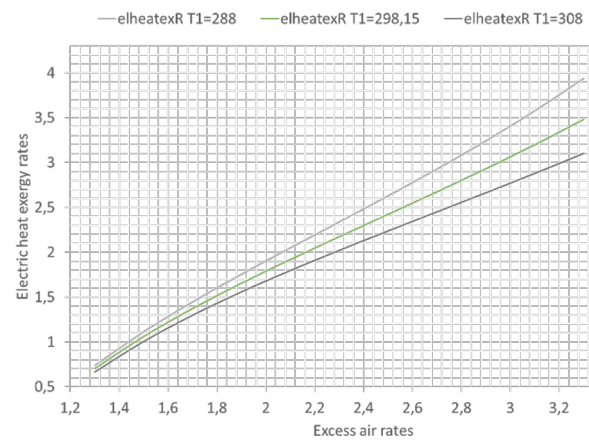


Fig. 7. Effects of excess air coefficient on electric and heat exergy coefficient for the recuperative cogeneration plant in various ambient temperatures.

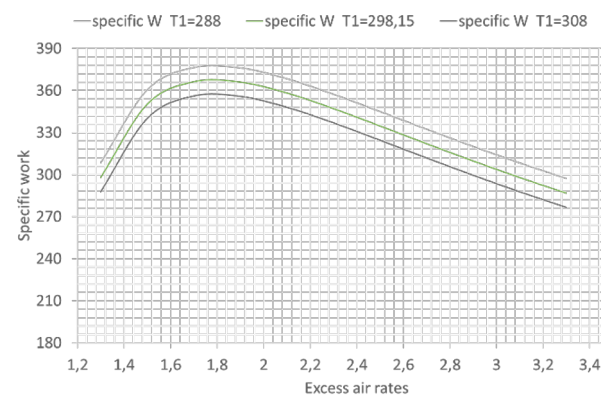


Fig. 8. Specific work as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures.

In Fig. 7, electric and heat exergy rates as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are obtained. Increase in ambient temperatures decreases the electric and heat exergy rates about % 20-30. However, increasing excess air coefficient from 1.3 to 3.3 increases the electric and heat exergy rates from 0.8 to 3-4.

In Fig. 8, specific work as a function of excess air coefficient for the recuperative cogeneration plant in

various ambient temperatures are obtained. Increase in ambient temperatures decreases the specific work about % 4-6. However, increasing excess air coefficient from 1.3 to 1.8 increases specific work from about %24. At the excess air coefficient of 1.8, there is the optimum point which means that the maximum specific work obtained at 1.8 excess air coefficient. However, increasing excess air coefficient over 1.8 decreases the specific work.

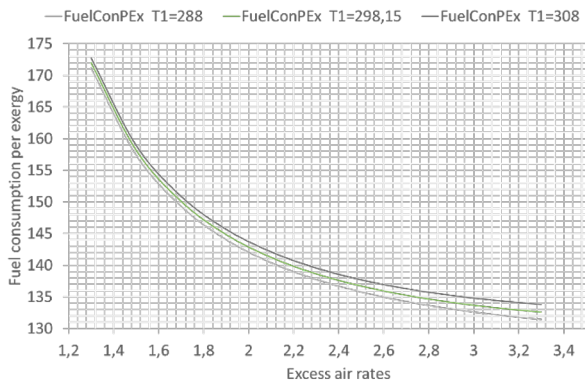


Fig. 9. Fuel consumption per exergy as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures.

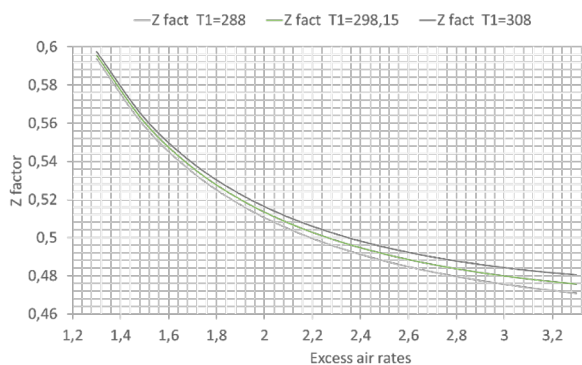


Fig. 10. Z factor as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures.

In Fig. 9, fuel consumption per exergy as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are obtained. Increase in ambient temperatures increases the fuel consumption per exergy about % 0.5-2. However, increasing excess air coefficient from 1.3 to 3.3 decreases the fuel consumption per exergy about %22.

In Fig. 10, Z factor as a function of excess air coefficient for the recuperative cogeneration plant in various ambient temperatures are obtained. Increase in ambient temperatures increases the Z factor about % 0.5-2. However, increasing excess air coefficient from 1.3 to 3.3 decreases the fuel consumption per exergy about %20.

4 Conclusions

In this study, an air fuel preheated (recuperative) cogeneration plant is analyzed to obtain the exergetic

performance and working conditions by using exergy analysis method and 1st and 2nd laws of thermodynamics. Energy efficiencies, combustion chamber and gas-turbine outlet temperatures, electric-heat exergy rates, specific works, total electric and heat energies and exergies, Z factor are calculated by taking various environmental temperatures and various excess air coefficient. The effects of the environmental temperatures and the excess air coefficient on the exergetic performance of the recuperative cogeneration plants were calculated, obtained, and discussed. For the best exergetic performance and working conditions, some recommendations can be done such as, the recuperative cogeneration plants can obtain and give the best solutions and can adapt to changing demands of heat and electric rates. Also, it was found that, lower ambient temperatures give better electric efficiency, but lower heat exergy and electric rates. However, higher excess air coefficient increase the performance of the recuperative (air fuel preheated) cogeneration plants.

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