*International Journal of Computational and Experimental Science and ENgineering (IJCESEN)*

*Vol. 9-No.2 (2023) pp. 165-169*
*http://dergipark.org.tr/en/pub/ijcesen*



***ISSN: 2149-9144***

**Research Article**

# Performance Analyses of Combined Cycle Power Plants

**Rabi KARAALİ***

Bayburt University, Fac. of Eng., Dep.of Mechanical Eng., Bayburt, Turkey.
***Corresponding Author** : **Email:** rabikar@gmail.com **ORCID:** 0000-0002-2193-3411

**Article Info:**

**DOI:** 10.22399/ijcesen.1310338
**Received :** 06 June 2023
**Accepted :** 20 June 2023

**Keywords**

Combine cycle
Exergy
Performances

**Abstract:**

In this article, different compressor pressure and different excess air rates for a gas turbine based combine cycle power plant with steam Rankine cycle as bottoming cycle were analyzed by using 1. and 2. laws of thermodynamics and exergy analyses methods to obtain the best performances of the cycle. Exergy efficiency of the cycle, net powers of the gas and steam turbines and the overall cycle, exergy loss of the components, the efficiencies of the components are obtained, compared and discussed. It was found that, increasing the compressor pressure increases exergy efficiency of cycle, gas turbine and total plant power, and the combustion chamber, the HRSG and the compressor efficiencies. However, increasing compression rates decreases steam turbine power, combustion chamber, steam turbine, and HRSG exergy losses and the gas turbine efficiency. Also, it is found that, increases in excess air ratios gives an optimum or a maximum exergy efficiency, at 2.5 excess air rate of the cycle.

## 1. Introduction

The environmental concerns regarding carbon emissions, rise in electricity demand with the rapid development of emerging economies and finite fossil fuel reserves have made the increased efficiency in energy conversions, the renewable energy sources and the recovery of previously unused energies very important [1, 2, 3]. To identify alternative sources of energy that can be used for power generation with minimal harmful effects to the environment is necessary. Today's environmental concerns are about the recovery and using of low-grade temperatures heat sources. Also, previously termed 'waste heat' in various industrial processes is now taken as a potential source for electricity generation. The CCPP technology includes two or more power cycles, to obtain high efficiency and to provide a decrease in pollutant emissions [4, 5, 6]. In power generation, gas turbine combined cycles have been used extensively. Also, combined cycles have the advantages low investment, operation and maintenance costs, suitability for plant operations and flexibility to fluctuations in demand. [7, 8].

Combined cycles include a topping cycle and a bottoming cycle. For the low temperatures, bottoming Organic Rankine Cycles (ORC) are another alternative, those have shown good performance. The organic working fluids for Rankine cycles has been proposed for different applications: for renewable energy, for heat recovery and they are commercially available [9, 10].

The Organic Rankine Cycle is a widely investigated for the using of low temperatures energy sources like geothermal, industrial waste heat, biomass, and solar which is reduced the capital and operation costs [10]. They have the advantages of the simplicity of construction and operation, smaller equipment sizes, and high modularity [10]. In literature, studies on the increasing efficiency of CCPP are about the increase of the efficiencies of gas turbines, steam turbines, and both cycles (topping and bottoming) [11], and the increase of the organic fluids impact on efficiency [10].

By applying reheat and by reducing the irreversibilities in HRSG, the efficiency of the Rankine cycle can be increased. Also, different factors may change the ORC performance such as the configuration of the system, thermophysical properties of working fluids, the temperature of the external source, the components efficiency, etc. The efficiency of the CCPPs can be improved by modifying the performance of the components. While Organic Rankine Cycles (ORC) are used to gain heat energy from different sources to generate power, the steam Rankine Cycles (SRC) are used to recover high temperature heat to generate power. Investigations for alternative, harmless, low emissions fuels to use in CCPPs can be found in literature [12, 13, 14].

In this study, gas turbine combined cycle with steam Rankine cycle was analyzed by using the 1., the 2. laws of thermodynamics and exergy analyses methods to obtain the best performances of the cycle by changing compression ratio and excess air rates.

## 2. Material and Methods

Gas turbine-based combine cycle power plant with steam Rankine cycle can be seen at Figure 1. Figure 1 shows that, the air is compressed to higher pressure, then it is combusted by fuel to obtain the combustion gas at 3. The gases at 3 are expanded to low pressure at 4. Gases at 4 enters the heat recovery steam generator to transfer heat to the steam. Steam at the outlet of HRSG at 8, is expanded in the steam-turbine at 9. Saturated water at the exit of the condenser at 10 is pumped to at 7.

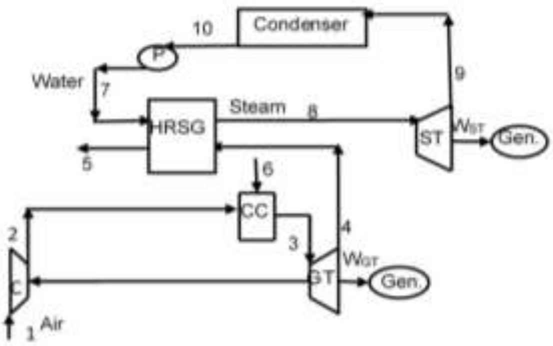


***Figure 1.*** *Gas turbine based combine cycle power plant with steam Rankine cycle as bottoming cycle.*

These assumptions were made for the analyses; the components are taken as a steady-state steady-flow systems, pressure drop is negligibly small, in kinetic and potential energies changes are negligible [11].

The energy equation;

$$\dot{Q}_{CV} - \dot{W}_{CV} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) - \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gz_{out}\right) = 0 \quad (1)$$

The conservation mass law for steady state;

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (2)$$

Efficiency of the system;

$$\eta = \frac{W + Q_{steam.}}{Q_{Fuel,inlet.}} \quad (3)$$

Electrical efficiency of the system;

$$\eta_{el} = \frac{W}{Q_{Fuel,inlet}} \quad (4)$$

For the calculations, the combustion was taken as ideally and completely [11]. The combustion is;

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

Physical exergy is;

$$e_{phyical} = (h - h_0)_{mixture} - T_0.(s - s_0)_{mixture} = \sum_j x_j\left[\int_{T_0}^{T} c_{p0j}(T)dT - T_0.\left(\int_{T_0}^{T} \frac{c_{p0j}(T)}{T}dT - \bar{R}\ln\frac{P_j}{P_0}\right)\right] \quad (5)$$

The chemical exergy is as [11];

$$\bar{e}_{chem,mixt} = \sum_i x_i\bar{e}_{chemical,i} + \bar{R}T_0\sum_i x_i \ln x_i \quad (6)$$

The total exergy are;

$$\bar{E} = \bar{E}_{phy} + \bar{E}_{chem} \quad (7)$$

***Table 1:*** *Equations of energies, mass, entropies of the components of gas turbine based combine cycle power plant with steam Rankine cycle [11].*

| Components | Mass Equation | Energy Equation | Entropy Equation |
|---|---|---|---|
| **Compressor** | $\dot{m}_1 = \dot{m}_2$ | $\dot{m}_1.h_1 + \dot{W}_C = \dot{m}_2.h_2$ | $\dot{m}_1.s_1 - \dot{m}_{1.}s_2 + \dot{S}_{gen,C} = 0$ |
| **Gas Turbine** | $\dot{m}_3 = \dot{m}_4$ | $\dot{m}_3h_3 = \dot{W}_{GT} + \dot{W}_C + \dot{m}_4h_4$ | $\dot{m}_3s_3 - \dot{m}_4s_4 + \dot{S}_{gen,GT} = 0$ |
| **HRSG** | $\dot{m}_4 = \dot{m}_5$ $\dot{m}_7 = \dot{m}_8$ | $\dot{m}_4h_4 + \dot{m}_7h_7 = \dot{m}_5h_5 + \dot{m}_8h_8$ | $\dot{m}_4s_4 + \dot{m}_7s_7 - \dot{m}_5s_5 - \dot{m}_8s_8 + \dot{S}_{gen,HRSG} = 0$ |
| **Steam Turbine** | $\dot{m}_8 = \dot{m}_9$ | $\dot{m}_8h_8 = \dot{W}_{ST} + \dot{W}_P + m$ | $\dot{m}_8s_8 - \dot{m}_9s_9 + \dot{S}_{gen,ST} = 0$ |
| **Combustion Chamber** | $\dot{m}_2 + \dot{m}_6 = \dot{m}_3$ | $\dot{m}_2h_2 + \dot{m}_6h_6 = \dot{m}_3h_3 + 0.02\dot{m}_6LHV$ | $\dot{m}_2s_2 + \dot{m}_6s_6 - \dot{m}_3s_3 + \dot{S}_{gen,CC} = 0$ |
| **Pump** | $\dot{m}_{10} = \dot{m}_7$ | $\dot{m}_{10}h_{10} = \dot{m}_7h_7 + \dot{W}_P$ | $\dot{m}_{10}s_{10} - \dot{m}_7s_7 + \dot{S}_{gen,P} = 0$ |
| **Condenser** | $\dot{m}_{10} = \dot{m}_9$ | $\dot{m}_9h_9 = \dot{m}_{10}h_{10} + \dot{Q}_c$ | $\dot{m}_9s_9 - \dot{m}_{10}s_{10} + \dot{S}_{gen,P} = 0$ |
| **Overall Cycle** | $\bar{h}_i = f(T_i)$ $\bar{s}_i = f(T_i, P_i)$ $\dot{m}_{air}h_{air} + \dot{m}_{fuel}LHV_{CH4} - \dot{Q}_{Loss,CC} - \dot{m}_{eg.,out}h_{eg.,out} - \dot{W}_{GT} - \dot{W}_{ST} - \dot{Q}_{Loss,c} = 0$ $\dot{Q}_{Loss,CC} = 0.02\dot{m}_{fuel}LHV_{CH4}$ | | |

For open systems exergy equation;

$$\sum_i \dot{m}_i.h_i - \sum_i T_0.S_i - \sum_j \dot{m}_j.h_j + \sum_j T_0.S_j + \sum \dot{Q}_k - \sum \dot{Q}_k.\frac{T_0}{T_k} - \dot{W} = \dot{E}_{loss} \quad (8)$$

In Table 1 equations of energy, mass, entropy of components of gas turbine based combine cycle power plant with steam Rankine cycle are given. In Table 2 the equations of exergies, exergy efficiencies, and performance criteria of components of gas turbine based combine cycle power plant with steam Rankine cycle are shown.

***Table 2:*** *The equations of exergies, exergy efficiencies, and performance criteria of components of gas turbine based combine cycle power plant with steam Rankine cycle [11].*

| Components | Exergy Equation | Exergy Efficiency |
|---|---|---|
| **Compressor** | $\dot{E}_{D,C} = \dot{E}_1 + \dot{W}_C - \dot{E}_2$ | $\eta_{ex,C} = \frac{\dot{E}_{out,C} - \dot{E}_{in,C}}{\dot{W}_C}$ |
| **Turbine** | $\dot{E}_{D,T} = \dot{E}_3 - \dot{E}_4 - \dot{W}_C - \dot{W}_{GT}$ | $\eta_{ex,GT} = \frac{\dot{W}_{net,GT} + \dot{W}_C}{\dot{E}_{in,T} - \dot{E}_{out,T}}$ |
| **HRSG** | $\dot{E}_{D,HRSG} = \dot{E}_4 - \dot{E}_5 + \dot{E}_7 - \dot{E}_8$ | $\eta_{ex,HRSG} = \frac{\dot{E}_{steam,HRSG} - \dot{E}_{wate}}{\dot{E}_{in,exhaust,HRSG} - \dot{E}_{out,e}}$ |
| **Steam Turbine** | $\dot{E}_{D,T} = \dot{E}_8 - \dot{E}_9 - \dot{W}_P - \dot{W}_{ST}$ | $\eta_{ex,ST} = \frac{\dot{W}_{net,ST} + \dot{W}_P}{\dot{E}_{in,ST} - \dot{E}_{out,ST}}$ |
| **Combustion Chamber** | $\dot{E}_{D,CC} = \dot{E}_2 + \dot{E}_6 - \dot{E}_3$ | $\eta_{ex,CC} = \frac{\dot{E}_{out,CC}}{\dot{E}_{in,CC} + \dot{E}_{fuel}}$ |
| **Pump** | $\dot{E}_{D,P} = \dot{E}_{10} + \dot{W}_P - \dot{E}_7$ | $\eta_{ex,P} = \frac{\dot{E}_{out,P} - \dot{E}_{in,P}}{\dot{W}_P}$ |
| **Condenser** | $\dot{E}_{D,c} = \dot{E}_9 - \dot{E}_{10}$ | $\eta_{ex,c} = \frac{\dot{E}_{in,c}}{\dot{E}_{out,c}}$ |
| **Overall Cycle** | Exergy efficiency | $\dot{E} = \dot{E}_{ph} + \dot{E}_{ch}$ $\dot{E}_{ph} = \dot{m}(h - h_0 - T_0(s - s_0))$ $\dot{E}_{ch} = \frac{\dot{m}}{M}\left\{\sum x_k \bar{e}_k^{ch} + \bar{R}T_0 \sum x_k \ln x_k\right\}$ $\eta_{ex} = \frac{\dot{W}_{net,GT} + \dot{W}_{net,ST}}{\dot{E}_{fuel}}$ |

## 3. Results and Discussions

The ambient conditions were taken as $P_0$=101.3 kPa and $T_0$=25 $^0$C, in this article. Compressor air flow is $m_{air}$=91.3 kg/sec, and fuel flow is $m_{fuel}$=1.64 kg/sec. The isentropic efficiency of the steam, gas turbines and compressor were taken as $\eta_{izST}=\eta_{izC}=\eta_{izGT}$=0.86. The compressor ratio is 10, temperature of steam $T_{steam}$=485.57 K. HRSG outlet temperature is taken as $T_{exh}$=426 K [11].

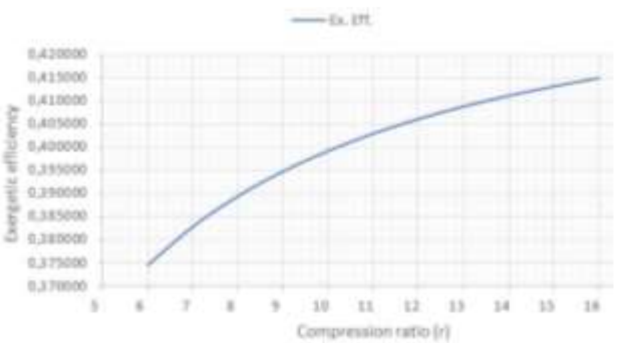


***Figure 2.*** *Variation of the exergy efficiency with compression ratios of CCPPs.*

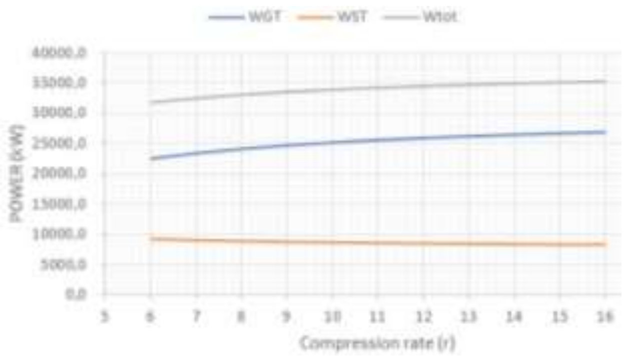


***Figure 3.*** *Variation of the power with compression ratios of CCPPs.*

In figure 2, variation of the exergy efficiency with pressure ratios of CCPPs is given. That is shown that, increasing pressure ratios from 6 to 16 increases exergy efficiency, about % 11 of the gas turbine based combine cycle power plant with steam Rankine cycle.

In figure 3, variation of the power with pressure ratios of CCPPs is given. Increasing compression rates, increases gas turbine and the total plant power, but decreases the steam turbine power. Increasing compression rates from 6 to 16 increases gas turbine, total plant power about % 15 and % 11. But decreases the steam turbine power about % 8.

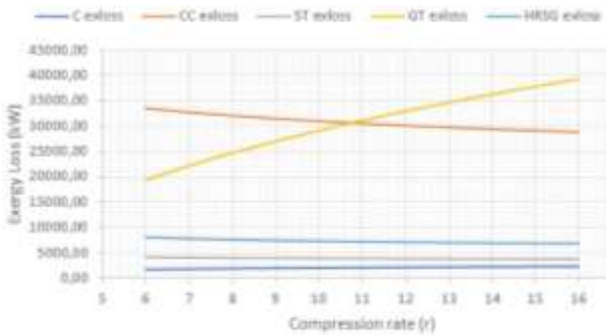


***Figure 4.*** *Variation of the exergy losses of the components with compression rates for CCPPs.*

In figure 4, variation of the exergy losses of components with compression rates for CCPPs are given. Increasing compression rates increases gas turbine and compressor exergy loss about % 76 and % 29, respectively. However, increasing compression rates decrease combustion chamber, steam turbine, and HRSG exergy losses about, % 12, % 8, % 16, respectively. In figure 5, variation of efficiencies of components with pressure ratios of CCPPs are given. That is seen, increasing compression rates increases the combustion, the HRSG and the compressor

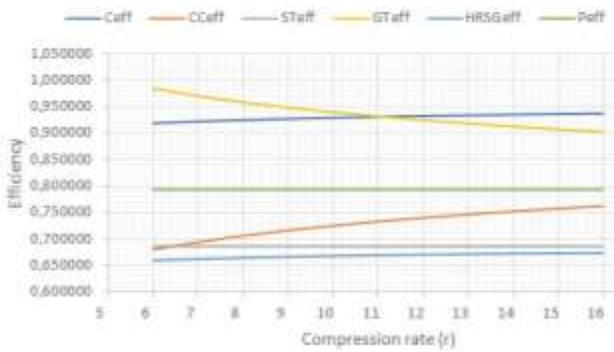


***Figure 5.*** *Variation of efficiencies of the components with pressure rates for CCPPs.*

efficiencies about % 11, % 2 and % 2, respectively. However, increasing compression rates decreases the gas turbine efficiency, about % 7, while the steam turbine, and the pump efficiencies stay constant.

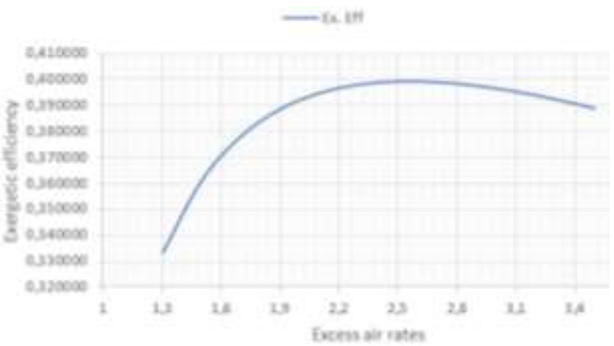


***Figure 6.*** *Variation of the exergy efficiency with excess air ratios of CCPPs*

In figure 6, variation of the exergy efficiency with excess air ratios of CCPPs is given. It can be seen, increasing excess air rates gives an optimum or maximum exergy efficiency, at 2.5 excess air ratio of the turbine based combine cycle power plant with steam Rankine cycle.

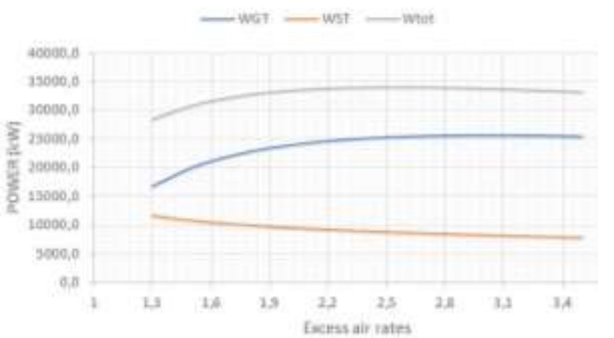


***Figure 7.*** *Variation of the net power of the turbines with excess air ratios of CCPPs.*

In figure 7, variation of net power with excess air ratios of the CCPPs is shown. That is seen, increasing excess air rates gives a maximum power point for gas turbine and total plant power at 2.9 and 2.5 excess air rates, respectively. But decreases the steam turbine power about % 34.

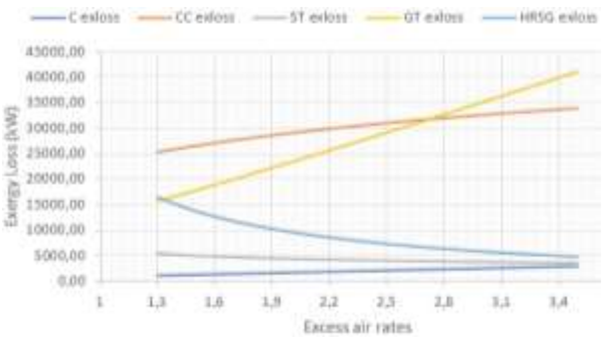


***Figure 8.*** *Variation of exergy loss of components with excess air ratios of CCPPs.*

In figure 8, variation of exergy loss of components with excess air ratios of CCPPs is given. An increase in excess air ratios increases gas turbine, combustion chamber and compressor exergy loss about % 161, % 34 and % 170, respectively. Also, increasing excess air rates decrease steam turbine, and HRSG exergy losses about, % 34, % 71, respectively.

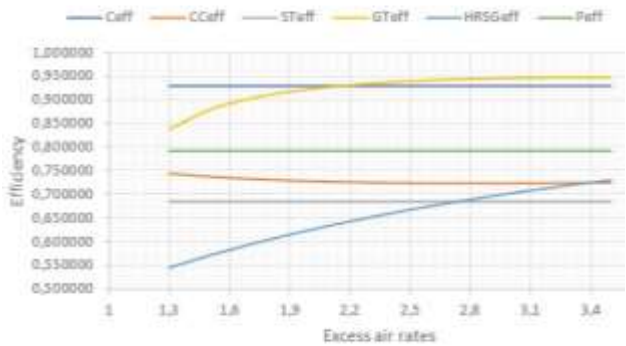


***Figure 9.*** *Variation of efficiencies of devices with excess air ratios of CCPPs.*

In figure 9, variation of efficiencies of devices with excess air ratios of CCPPs can be seen. An increase in excess air ratios increases gas turbine, and HRSG efficiencies % 13 and % 34, respectively. However, increasing excess air ratio has an affect to decrease combustion chamber efficiency, about % 3, while compressor, the steam turbine, and the pump efficiencies stay constant.

## 4. Conclusions

In this article, different compressor pressures and excess air ratios for a gas turbine based combine cycle power plant with steam Rankine cycle as bottoming cycle are analyzed by using 1. and 2. laws of thermodynamics and exergy analyses methods to obtain the best performances of the cycle. Exergy efficiency of the cycle, net powers of gas turbine, steam turbine and the cycle, exergy loss of the components, the efficiencies of the components are obtained, compared and discussed. That is found, an increase in compression rate increase exergy efficiency of this cycle, gas turbine and the total plant power, and the combustion chamber, the HRSG and the compressor efficiencies. However, increasing compression rates decreases the steam turbine power, combustion chamber, steam turbine, and the HRSG exergy losses and the gas turbine efficiency. Also, that is found, increasing excess air ratios from 1.3 to 3.5 gives an optimum or a maximum exergy efficiency, at 2.5 excess air ratio of the cycle. Increasing excess air ratios, increases gas turbine, combustion chamber and compressor exergy losses, but decreases steam turbine, and HRSG exergy losses.

## Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

## References

[1] Keven A., Karaali R., (2015). Investigation of an Alternative Fuel for Diesel Engines. *Acta Physica Polonica A*, 128(2B);282 – 286.

[2] Karaali, R., (2016). Thermodynamic Analysis of a Cascade Refrigeration System. *Acta Phys. Pol. A* 130(1);101-106. DOI: 10.12693/APhysPolA.130.101

[3] Karaali, R., (2016). Exergy Analysis of a Combined Power and Cooling Cycle. *Acta Phys. Pol. A* 130(1);209-213. DOI: 10.12693/APhysPolA.130.209

[4] Karaali, R. (2010). *Thermoeconomic optimization of cogeneration power plants* (Doctoral dissertation, PhD Thesis. Kocaeli Univ).

[5] Karaali R., Öztürk İ.T. (2017). Performance Analyses of Gas Turbine Cogeneration Plants. *ISI Bilimi ve Teknigi Dergisi-Journal of Thermal Science and Technology*. 37(1);25 – 33.

[6] Karaali R., Keven A., (2022). Evaluation of Four Different Cogeneration Cycles by Using Some Criteria. *Applied Rheology*, 32(1);122 – 137.

[7] Jiangfeng Wang, Yiping Dai, and Lin Gao, (2008). Parametric analysis and optimization for a combined power and refrigeration cycle. *Applied Energy*. 85;1071–1085

[8] Christoph Koch, Frank Cziesla and George Tsatsaronis, (2007). Optimization of combined cycle power plants using evolutionary algorithms. *Chemical Engineering and Processing* 46;1151–1159

[9] M. A. Javadi, S. Hoseinzadeh, M. Khalaji and R. Ghasemiasl, (2019). Optimization and analysis of exergy, economic, and environmental of a combined cycle power plant. *Sadhana* 44;121. https://doi.org/10.1007/s12046-019-1102-4

[10] Keyvan Bahlouli, (2018) Multi-objective optimization of a combined cycle using exergetic and exergoeconomic approaches. *Energy Conversion and Management*. 171;1761–1772. https://doi.org/10.1016/j.enconman.2018.06.100

[11] Bejan, A., Tsatsaronis, G,, Moran, M. (1996). Thermal Design and Optimization. Danvers, Massachusetts: Wiley Pub.

[12] Şanlı, H., Alptekin, E., Çanakç, M., (2022). Using low viscosity micro-emulsification fuels composed of waste frying oil-diesel fuel-higher bio-alcohols in a turbocharged-CRDI diesel engine, *Fuel*, 308;1-13.

[13] Alptekin, E., Şanlı, H., Çanakç, M., (2019). Combustion and performance evaluation of a common rail DI diesel engine fueled with ethyl and methyl esters, *Applied Thermal Engineering*, 149;180-191.

[14] Şanlı, H., (2018). An experimental investigation on the usage of waste frying oil-diesel fuel blends with low viscosity in a Common Rail DI-diesel engine. *Fuel*, 222;434-443.