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

Vol. 10-No.1 (2024) pp. 85-90

http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Exergetic Analyses of Detonation Engine Cogeneration Plants

Bahar ÇAKMAK[1], Rabi KARAALİ[2]*

[1]Bayburt University, Engineering Fac., Mechanical Eng. Department M.S., Merkez, Bayburt, Turkey.
Email: caklmakbahar61@hotmail.com - **ORCID:**0009-0002-3116-9178

[2]Bayburt University, Engineering Fac., Department of Mechanical Eng., Merkez, Bayburt, Turkey.
***Corresponding Author: Email:** rabikar@gmail.com - **ORCID:** 0000-0002-2193-3411

Article Info:

DOI: 10.22399/ijcesen.234
Received : 11 November 2023
Accepted : 04 March 2024

Keywords

Detonation
Exergy
Cogeneration

Abstract:

Efficiency improvements are very important in all research and technology. Detonation engines are high technology devices. In the last decades they attracted attention by many researchers. However, detonation engines for cogeneration are not researched efficiently. This article is about the detonation engines cogeneration cycles which analysed by using 1. and 2. law of thermodynamics and exergy analyses methods by the authors. The exergetic performance analyses, their advantage and disadvantages of the ZND-HRSG detonation engine cogeneration cycles were obtained. The exergetic performance analyses were done for various excess air rates to obtain the variations of the combustion exit pressures and temperatures, exergy efficiencies, electric heat rates, SFC and other parameters of their performance. Also, an optimization analysis was done for the ZND-HRSG by searching the optimum values for different excess air rates. The results showed that, the ZND-HRSG cycle have the optimum values of the performance at 1.6-1.8 of the excess air rates.

1. Introduction

Efficiency improvements are very important in all research and technology. Alternative fuels, zero emission cycles, cogeneration, trigeneration, efficiency improvements are some of the main research areas in our days [1, 2, 3, 4]. Also, better components design, environmental technologies, space vehicles, cryogenic cycles, and refrigeration are important research areas in engineering [5, 6, 7, 8]. Combustion efficiency is vital for all technological process and environment. Deflagration is a subsonic speed combustion process that flames obtained in this process. Deflagration process is used such as Otto, Brayton Diesel cycles. Detonation engines are high technology devices that considered promising technology by the researchers in our days. However, using detonative engines for cogeneration are not researched efficiently in our days. The main method to obtain PGC-pressure gain combustion is detonative combustion. With detonative combustion 30% higher thermal efficiency can be obtained than the deflagration process. Detonative combustions are based on supersonic mode of combustions. Detonative combustions cause rapid burning (thousands of times faster than deflagration process). Detonative combustions are shock front driven and detonation engines very good shown by ZND (Zeldovich–von Neumann–Doring) cycle [9, 10].

Cogeneration plants are exergy efficient, compact, economic, fuel flexible, environmental and small sized cycles. Because of these advantages over conventional systems, cogeneration cycles have become widespread on the world.

Because of the metallurgical reasons, maximum temperature for gas turbines must be below than 1600 K. By using 2-4 times of the air theoretically required, these temperatures can be obtained. Air properties are very important and effective on exhaust gas properties and working conditions.

Keven, (2023) have investigated three different cogeneration cycles' exergetic performance and found that using recuperators were improving their efficiency and performance [11]. The three various plants were air fuel heating, air heating and basic cogeneration cycles. She found that excess air rates were more effective than the pressure ratio and ambient temperatures. She also, concluded that decreasing inlet air temperatures by using absorption cooling or by other methods, if possible, should be considered. For obtaining optimum working conditions, and maximum efficiencies an optimization process should be carried out. For good and improved performance, the design of the cycles is very important for working conditions. Needless equipment decreases the performance and advantages of the cycle. Also, Karaali and Keven, (2022) investigated four different cogeneration cycles' efficiencies, the effect of absorption cooling of inlet air of compressor and the effect of adding recuperators into these cycles, on the working conditions [12, 13, 14]. They found that absorption cooling by using waste heat can help to improve the efficiencies and the working conditions of the four cogeneration systems. By absorption cooling of inlet air less work is spent for compression and about %1-3 efficiency could be improved by that method. They also investigated the effect of excess air and compression ratios on the performance of cogeneration plants. They found the optimum working conditions and optimum compression and excess air values. Keven, (2023) in her article about the detonative engine cogeneration plants has investigated the performance for various pressure rates. She found the various pressure rates effect on the combustion exit pressures and temperatures, exergy and energy efficiencies, SFC, electric efficiency, and other performance parameters. She has showed ZND cogeneration cycles' advantages for production power and heat [15,16].

2. Material and Methods

In Figure 1, the figure of the ZND-HRSG detonative engine cogeneration cycle is given. Ambient air is taken for compression and then the compressed air after the check valve is given in to the pulse detonation chamber. After detonative combustion exhaust gases are given in to the HRSG to produce steam. The exhaust gases are at 2000-3000 K temperatures at the inlet of the HRSG. At the exit of the HRSG the temperatures of the exhaust gases are about 1500 K. By giving some of the heat energy of the exhaust gases to produce steam the exhaust gases are cooled because of the gas turbine's metallurgical reason. Some of the exhaust gases' energy is used to produce mechanical energy in the gas-turbine. The mechanical energy is used to produce electricity in a generator. Exhaust gas at exit of the gas turbine is at low pressure, but high temperatures about 750-950 K, which is available to produce steam in the HRSG. Equations for the components of ZND-HRSG detonative engine cogeneration cycle are shown in Table 1. Equations about exergy, efficiency, and performance for the components of the ZND-HRSG detonation engine cogeneration system are given in Table 2.

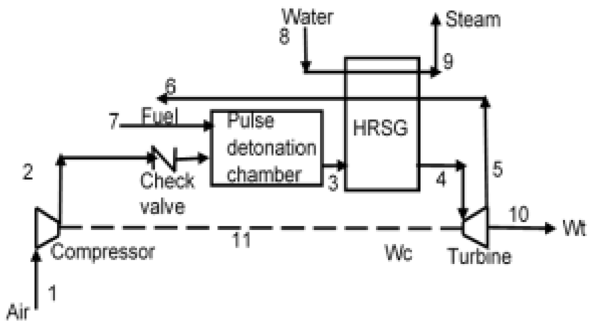

***Figure 1.** The figure of the ZND-HRSG detonative engine cogeneration cycle.*

The detonative combustion for the pulse detonation chamber;

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

The equations of Table 1 and Table 2 are used to write the code of a FORTRAN computer program for the calculations. In this study, the ambient conditions were as P_0=101.30 kPa and T_0=298.15 K, and fuel mass flow rates taken as $m_{fuel,CC}$=1.640 kg/s. Turbine's and compressor's isentropic efficiencies of the plant were as, $\eta_{iz,\ C}=\eta_{iz,\ T}$=0.860, the steam temperature is as $T_{steam,\ HRSG}$=485.57 K. The exit temperatures of the exhaust gases were $T_{exhaust,\ HRSG}$=426.0 K [17].Temperatures of ZND-HRSG is given by equation 1

$$T = T^{*}\left(\frac{(\gamma+1)M}{1+\gamma M^2}\right)^2 \quad (1)$$

***Table 1.** Equations for the components of the ZND-HRSG detonative engine cogeneration system [15, 16].*

Devices	Mass Equations	Energy Equations	Entropy Equations
Compressor	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1.h_1 + \dot{W}_C = \dot{m}_2.h_2$	$\dot{m}_1.s_1 - \dot{m}_1.s_2 + \dot{S}_{gen,C} = 0$
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	$\dot{m}_3 = \dot{m}_4$ $\dot{m}_5 = \dot{m}_6$ $\dot{m}_8 = \dot{m}_9$	$\dot{m}_3h_3 + \dot{m}_5h_5 + \dot{m}_8h_8 = \dot{m}_4h_4 + \dot{m}_8h_8 + \dot{m}_9h_9$	$\dot{m}_3s_3 + \dot{m}_5s_5 + \dot{m}_8s_8 - \dot{m}_4s_4 - \dot{m}_6s_6 - \dot{m}_9s_9 + \dot{S}_{gen,HRSG} = 0$
Combustion Chamber	$\dot{m}_2 + \dot{m}_7 = \dot{m}_3$	$\dot{m}_2h_2 + \dot{m}_7h_7 = \dot{m}_3h_3 + 0.02\dot{m}_7LHV$	$\dot{m}_2s_2 + \dot{m}_7s_7 - \dot{m}_3s_3 + \dot{S}_{gen,CC} = 0$
Overall Cycle	$\bar{h}_i = f(T_i)$ $\dot{m}_{air}h_{air} + \dot{m}_{fuel}LHV_{CH4} - \dot{Q}_{Loss,CC} - \dot{m}_{eg.,out}h_{eg.,out} - \dot{W}_T - \dot{m}_{steam}\left(h_{water,in} - h_{steam,out}\right) = 0$ $\dot{Q}_{Loss,CC} = 0.02\dot{m}_{fuel}LHV_{CH4}$ $\bar{s}_i = f(T_i, P_i)$		

Table 2. *Equations about exergy, efficiency, and performance for the components of the ZND-HRSG detonation engine cogeneration system [17].*

Devices	**Exergy Equations**	**Exergy Efficiencies**
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	$\dot{E}_{D,T} = \dot{E}_4 - \dot{E}_5 - \dot{W}_C - \dot{W}_T$	$\eta_{ex,T} = \frac{\dot{W}_{net,T} + \dot{W}_C}{\dot{E}_{in,T} - \dot{E}_{out,T}}$
HRSG	$\dot{E}_{D,HRSG} = \dot{E}_5 - \dot{E}_6 + \dot{E}_3 - \dot{E}_4 + \dot{E}_8 - \dot{E}_9$	$\eta_{ex,HRSG} = \frac{\dot{E}_{steam,HRSG} - \dot{E}_{water,HRSG}}{\dot{E}_{in,exh.,HRSG} - \dot{E}_{out,exh.,HRSG}}$
Combustion Chamber	$\dot{E}_{D,CC} = \dot{E}_2 + \dot{E}_7 - \dot{E}_3$	$\eta_{ex,CC} = \frac{\dot{E}_{out,CC}}{\dot{E}_{in,CC} + \dot{E}_{fuel}}$
Overall Cycle	The electrical heat ratio	$EHR = \frac{\dot{W}_{net}}{Q_{net}}$
	SFC-Specific Fuel Consumption	$SFC = 3600.\frac{\dot{m}_{fuel}}{\dot{W}_{net}}$
	Exergy efficiency	$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch}$ $\dot{E}_{ph} = \dot{m}(h - h_0 - T_0(s - s_0))$ $\dot{E}_{ch} = \frac{\dot{m}}{M}\left\{\sum x_k \bar{e}_k^{ch} + \bar{R}T_0 \sum x_k \ln x_k\right\}$ $\eta_{ex} = \frac{\dot{W}_{net,T} + (\dot{E}_{s.,HRSG} - \dot{E}_{w,HRSG})}{\dot{E}_{fuel}}$

Entropy of –HRSG is given by equation 2

$$\Delta s = c_p \ln\left[M^2\left(\frac{\gamma+1}{1+\gamma M^2}\right)^{\frac{\gamma+1}{\gamma}}\right] \quad (2)$$

Some of data of the detonative and deflagration combustive reactions for fuel, air, exhaust gases were calculated, with NASA CEA code (https://cearun.grc.nasa.gov/) [18]. The approximation of the exhaust properties was adopted for the exergy analyses [18].

3. Results and Discussions

In Figure 2, the combustion chamber exit pressures with excess air values of the ZND detonation engine cogeneration plants in various compression rates are given. The results were obtained for different compression rates (r=2, r=3, r=4, r=5, r=6, r=7 and r=8). When the excess air values increase, pressure of the detonation combustion chamber decreases. However, increasing compression values increase the exit pressures. While r = 2, approximately 28 Bar combustion chamber pressure showed an excess air value of 1.2, at r = 3, the air excess values was 34 Bar at 1.2 at 37 Bar detonation combustion chamber outlet pressure.

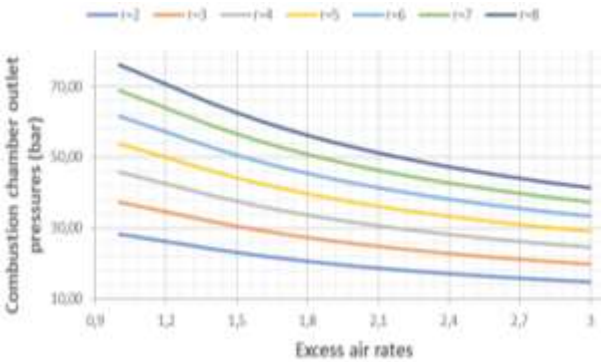

Figure 2. *Effects of excess air values on combustion chamber exit pressures for the ZND detonation engine cogeneration plants in various compression rates.*

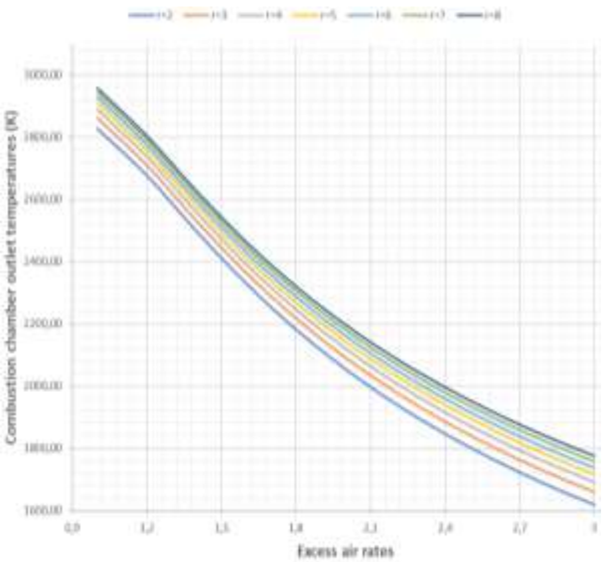

Figure 3. *Effects of excess air values on combustion chamber exit temperatures for the ZND-HRSG detonative engine cogeneration plants in various compression rates.*

In Figure 3, effects of excess air ratio on combustion chamber exit temperatures for the ZND-HRSG detonation engine cogeneration plants in various compression rates are given. The Figure 3, shows that the detonation combustion chamber exit temperature (K) for different compression ratios tends to decrease as the excess air number increases. It can be seen that while the air excess values are 1.2 at the r=2 compression ratio, the detonation combustion chamber temperature is around 2680.00 K. In Figure 4, effects of excess air values on the exergy efficiency for the ZND detonative engine cogeneration plants are obtained. Increasing excess air coefficient from 1.2 to 1.75 the system's exergy efficiency was increasing. The optimum (maximum) exergy efficiency was obtained at 1.75

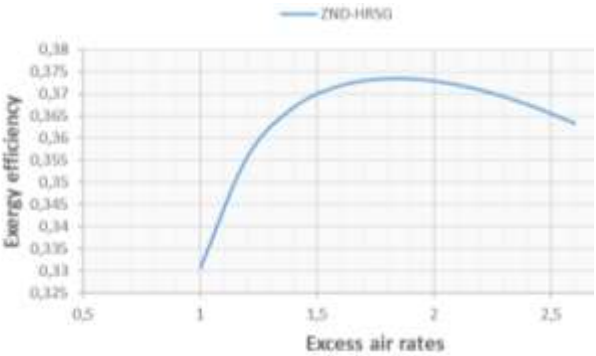

Figure 4. *Effects of excess air values on the exergy efficiency for the ZND detonation engine cogeneration plants.*

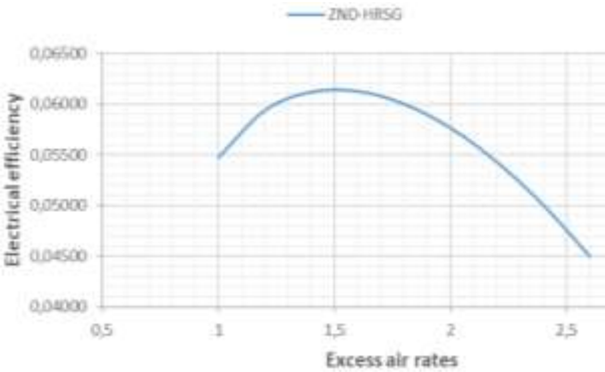

Figure 5. *Effects of excess air values on electrical efficiency for the ZND-HRSG detonative engine cogeneration plants.*

excess air values. After these values, exergy efficiency tends to decrease as the air excess values increase. In Figure 5, effects of excess air values on electrical efficiency for the ZND-HRSG detonative engine cogeneration plants are given. It is seen in Figure 5, ZND-HRSG detonative engines, electrical efficiency reaches the maximum value when the air excess coefficient was 1.5. After this value, as air excess values increases, electrical efficiency begins to decrease.

In Figure 6, effects of excess air values on specific fuel consumptions for the ZND-HRSG detonative engine cogeneration plants are given. It is seen in Figure 6, as the excess air values increases, specific fuel consumption tends to first decrease and then increase. As can be seen in the figure, minimum specific fuel consumption is achieved when the excess air values are 1.5.

In Figure 7, effects of excess air values on electric heat rate for the ZND-HRSG detonative engine cogeneration plants are given. As the air excess values increases, a certain amount of electrical heat ratio increases, and then the heat decreases. When we look at the range where it shows the maximum value at 0.2 electrical heat rates, occurs at an excess air value of 1.3.

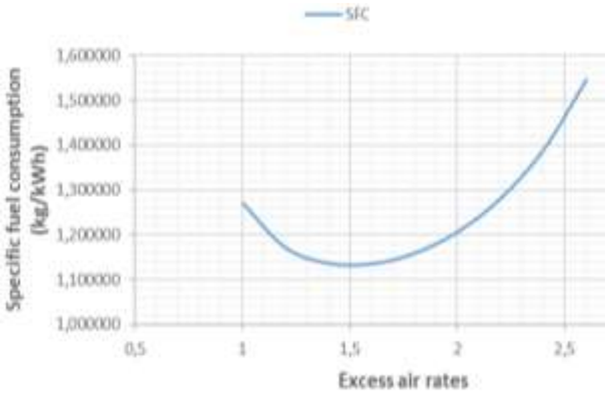

Figure 6. *Effects of excess air values on specific fuel consumptions for the ZND-HRSG detonative engine cogeneration plants.*

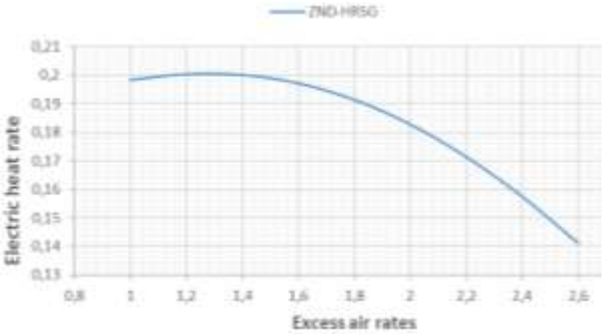

Figure 7. *Effects of excess air values on electric heat rate for the ZND-HRSG detonative engine cogeneration plants.*

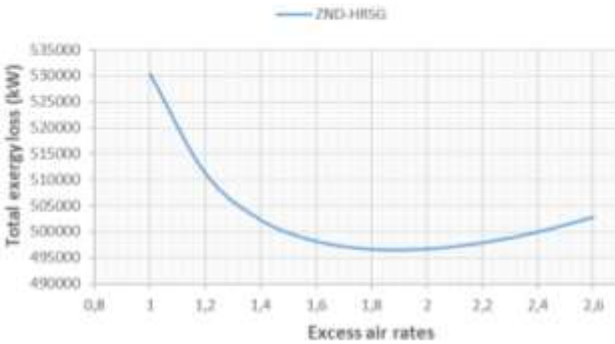

Figure 8. *Effects of excess air values on total exergy loss for the ZND-HRSG detonative engine cogeneration plants.*

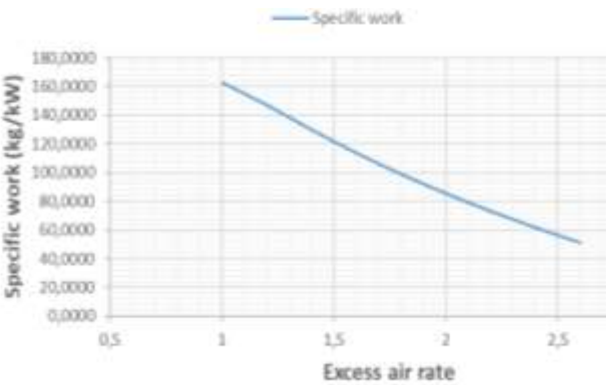

Figure 9. *Effects of excess air values on specific work for the ZND-HRSG detonation engine cogeneration plants.*

In Figure 8, effects of excess air values on total exergy loss for the ZND-HRSG detonative engine cogeneration cycles are given. When excess air values increase, there is an increase in exergy loss after a decrease up to a certain value. The excess air coefficient value with the lowest total exergy loss corresponds to the range of 1.8 to 1.9.

In Figure 9, effects of excess air values on specific work for the ZND-HRSG detonation engine cogeneration cycles are obtained. That is concluded, increases in excess air values decrease the specific work.

4. Conclusions

In ZND-HRSG detonation engines, as the excess air values increase, pressure and outlet temperature of the detonation combustion chamber decrease. Maximum turbine power and electrical efficiency are reached the values that the excess air rate is 1.5, and maximum exergy efficiency is reached when the average excess air coefficient is 1.75. After these values, as the air excess coefficient increases, turbine power, electrical efficiency and exergy efficiency tend to decrease. Minimum specific fuel consumption is reached at values that the excess air coefficient is 1.5. And when the average excess air rates was 1.75, the minimum fuel spent for exergy value is reached. After these values, as the excess air coefficient increases, specific fuel consumption and the value of fuel spent on exergy tend to increase.

In conclusion, ZND-HRSG detonation engines cogeneration systems are new technology, and in this study the best (optimum) working conditions are obtained and discussed.

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 rights 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]Karaali, R., Oztürk, I.T. (2016). Thermodynamic Optimization of a Zero CO2 Emission Cogeneration Cycle. *Fresenius Environmental Bulletin*, 25(12): 5729- 5738

[2]Keven, A., Karaali, R. (2015). Investigation of an Alternative Fuel for Diesel Engines. *Acta Physica Polonica A*, 128(2B);282 – 286. DOI:10.12693/APhysPolA.128.B-282

[3]Keven, A., Karaali, R. (2022). Analysis of Some Tribological Properties of Hazelnut Oil in Gasoline engines. *Erzincan University Journal of Science and Technology.*15;75–83. DOI:10.18185/erzifbed.1199745

[4]Şanlı H., Çanakçı, M., Alptekin E., Türkcan, A., Özsezen, A.N., (2015). Effects of waste frying oil-based methyl and ethyl ester biodiesel fuels on the performance, combustion and emission characteristics of a DI diesel engine. *Fuel*, 159, 179-187.

[5]Alptekin E., Çanakçı M., Şanlı H., (2014). Biodiesel production from vegetable oil andwaste animal fats in a pilot plant. *Waste Management*, 34, 2146-2154.

[6]Keven, A., Öner, C. (2023.) Emission and Lubrication Performance of Hazelnut Oil as A Lubricant. *International Journal of Computational and Experimental Science and Engineering,* 9;219 – 224. DOI: 10.22399/ijcesen.1321604

[7]Atasbak, M., Karaali, R., Keven, A. (2022). Exergy analyses of two and three stage cryogenic cycles. *Applied Rheology,* 32; 194 – 204. DOI:10.1515/arh-2022-0134

[8]Keven, A. (2023). Exergy Analyses of Vehicles Air Conditioning Systems for Different Refrigerants. *International Journal of Computational and Experimental Science and Engineering,* 9; 20 – 28. DOI: 10.22399/ijcesen.1258770

[9] Bellini, R., and Lu, F.K.(2010). Exergy Analysis of a Pulse Detonation Power Device. *Journal of Propulsion and Power.* 26(4); DOI:10.2514/1.44141

[10]Bellini, R. (2010). *Ideal Cycle Analysis of a Regenerative Pulse Detonation Engine for Power Production.* PhD Thesis. The University of Texas at Arlington USA.

[11]Keven, A. (2023). Exergetic performance analyses of three different cogeneration plants. *Open Chemistry,* 21;1 – 13. DOI: 10.1515/chem-2022-0295.

[12]Karaali, R., Keven, A. (2022). Performance Analysis of Air Fuel Heating Effects on Cogeneration cycles. *European Journal of Science and Technology*, 43;91 – 96. DOI: 10.31590/ejosat.1199414

[13]Karaali R., Keven, A. (2022). Evaluation of four different cogeneration cycles by using some criteria. *Applied Rheology*, 32;122 – 137. DOI: 10.1515/arh-2022-0128

[14]Karaali, R., Keven, A. (2022). Exergy Analysis of Inlet Air Absorption Cooling Effects on Basic Cogeneration Systems. *European Journal of Science and Technology.* 43;97 – 103. DOI: 10.31590/ejosat.1199382

[15]Keven, A. (2023). Performance analyses of detonation engine cogeneration cycles. *Open Chemistry,* 21;1 – 9. DOI: 10.1515/chem-2022-0313.

[16]Çengel, Y., Boles, M.A. (2001). *Thermodynamics: an engineering approach.* McGraw-Hill.
[17]Bejan, A., Tsatsaronis, G., Moran, M. (1996). *Thermal design and optimization*. Wiley Pub, New York.
[18]https://cearun.grc.nasa.gov/