EXERGY ANALYSIS OF A GAS TURBINE PERFORMANCE WITH EFFECT CYCLE TEMPERATURES

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ABSTRACT

To examine the degradation of energy during a practice, the production of entropy and the loss of work opportunities, exergy is analyzed. This analysis provides an alternative plan to ensure superior performance of a power plant. This study performed an exergetic analysis for a Baiji plant with a gas-turbine of capacity 159-MW. Each component of the system was tested in accordance with the laws of mass and energy conversion. The aspects under consideration were the quantitative exergy balance for the entire system and for each component, respectively. At different temperatures, rate of irreversibility of system components, efficiency of exergy and the efficiency flaws were highlighted for each component and for the whole plant. The exergy flow of a material is classified into the groupings of thermal, mechanical and chemical exergy in this study and a stream of entropy-production. Fuel oil of low heating value of 42.9 MJ/kg was used as the fuel. The evaluation addressed the question of how the fluctuations in cycle temperatures influence the exergetic efficiency and exergy destruction in the plant. The rate of exergy destruction in the turbine was around 5.4% whereas that in the combustion chamber was about 36.4%. When a 14°C rise was done in the temperature, exergy efficiency for the combustion chamber and the turbine was calculated to be 45.43% and 68.4%, respectively. According to the results of the study, the combustion chamber and turbine are found to be chief means of irreversibilities in the plant. Also, it was identified that the exergetic efficiency and the exergy destruction are considerably dependent on the alterations in the turbine inlet temperature. On the basis of these results, recommendations are presented for advancement of the plant.

Keywords: *Gas turbine, efficiency; exergy, irreversibility, performance.*

1. INTRODUCTION

Presently, a number of researchers such as Cengel and Boles [1]; Jones and Dugan [2]; Moran and Shapiro [3]; Aljundi [4], have chosen the topic of *"exergy analysis in thermal design"* and have provided considerable amount of literature on it. Basically the performance of a system is assessed by an exergy analysis as it is derived from the second law of thermodynamics which makes it rise above the limitations of an energy-based analysis. Exergy is annihilated in the system rather than conserved. The chief source of inefficiency of a system is the amount of irreversibility which is the exergy destruction. Thus, in a thermal system the location, the amount and the cause of thermodynamic deficiencies are determined by the exergy analysis evaluating the degree of exergy destruction [5-7]. The entropy-generation of the components is precisely calculated in the exergy analysis and this enables us to forecast the thermodynamic performance of an energy system and the efficiency of the system components [8].

There has been a rapid development in advanced approaches to study the intricate energy systems based on the second law of thermodynamics. This is due to the keen interest showed by researchers in energy efficiency and conservation. The phenomenon of exergy gives rise to one such performance analysis. The shortcomings of an energy-based study have been removed by an exergy-based system analysis. Exergy differs from energy as the former is destroyed rather than conserved in a system. Therefore, the position, amount and causes of system deficiencies have been determined by an exergy analysis used to evaluate the quantity of exergy destruction [9-12]. Such an analysis ensures the distinction between energy lost to the environment and internal irreversibility of the process. It is due to this that thermodynamic evaluation of energy conservation can be performed in an exergetic analysis [13-15]. Thermal processes are enhanced and irreversibilities in system components are measured effectively due to the statistics provided. Also, the role played by irreversibilities in the gross irreversibility of the whole plant is studied. Moreover, it provides a chance to reflect on the economic and developmental aspects for superior efficiency. Our research involved conducting an exergetic analysis for a 159-MW gas-turbine Baiji plant situated at Baiji, Iraq. Each component was studied under the light of laws of energy and mass conservation along with the air preheated (heat exchanger). We utilized the exergy balance equation developed by Oh et al. [16] for this analysis and for each component a quantitative exergy balance was derived cautiously.

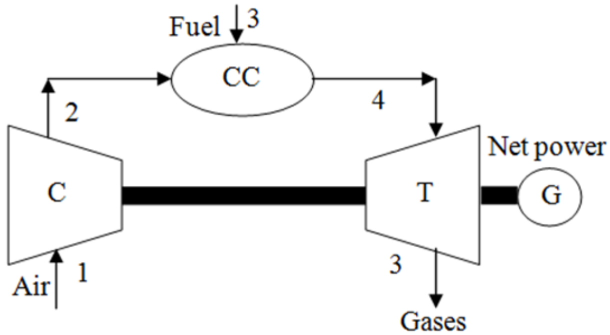

Figure 1. Baiji gas turbine plant

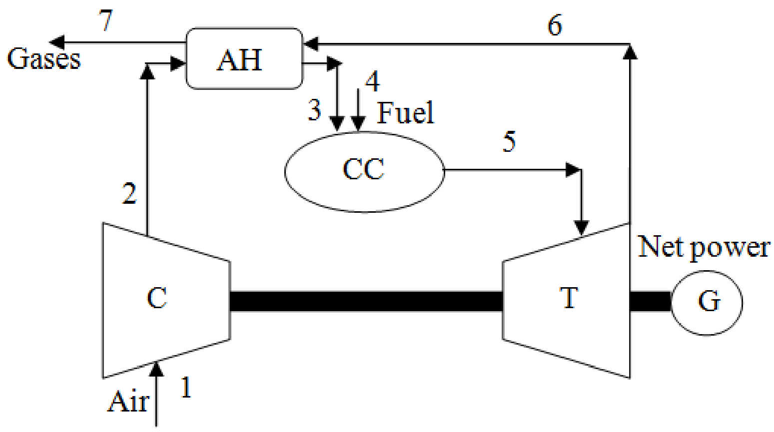

Figure 2. Air pre-heater gas turbine plant

2. DESCRIPTION OF GAS TURBINE PLANT

Figure 1 gives the overview of the structure, working, exergy flows and the assumptions for analysis of a 159-MW gas turbine system. The components of the system include an air-compressor (C), a combustion chamber (CC), and a gas turbine (GT). Air enter to the compressor at 25°C has a mass flow rate of 505 kg/s. 25°C and 1.013 bar is the temperature and pressure of the air input, respectively. The compressor has isentropic efficiency of 83% and amplifies the pressure up to 11.7 bar. The turbine has the inlet temperature of 1143°C and an isentropic efficiency of 88%. According to Figure 2, the efficiency of the air pre-heater heat exchanger is 85%. The pressure of the hot gas exhaust from the air pre-heater is 1.032 bar. The flow streams through both the air pre-heater and the combustion chamber experiences a pressure drop of 3% of the inlet pressure. At a temperature of 46°C and pressure of 22 bar, the fuel (fuel oil) is introduced.

3. FORMULATION OF EXERGY-BALANCE EQUATION

Cortés and Rivera, [17] suggests that the thermal and mechanical components of thermo-mechanical exergy flow can be separated. Both the laws of thermodynamics can be employed to derive the following common exergy balance equation which can be related to any component of a thermodynamic system [16]:

$$E_{in}^{m} - E_{out}^{m} = \left(E_{in}^{T} - E_{out}^{T}\right) + \left(E_{in}^{M} - E_{out}^{M}\right) \tag{1}$$

In this equation, the inflow and outflow of the exergy flow streams in the component of the plant are specified by subscripts in and out, respectively. For an ideal gas having a constant specific heat, the thermal and mechanical components of the exergy flow can be shown as [18]:

$$E^{T} = m^{\bullet} c_p \left[\left(T - T_{ref}\right) - T_{ref} \ln\left(\frac{T}{T_{ref}}\right)\right] \tag{2}$$

$$E^{M} = m^{\bullet} R T_{ref} \ln\left(\frac{P}{P_{ref}}\right) \quad (3)$$

Following is the general exergy-balance equation drawn from the definition of decomposition as given in Equation (1) [16]:

$$E^{W} = E^{Ch} + \left(\sum_{in} E_{in}^{T} - \sum_{out} E_{out}^{T}\right) + \left(\sum_{in} E_{in}^{M} - \sum_{out} E_{out}^{M}\right) + T_{ref}\left(\sum_{in} S_{in} - \sum_{out} S_{out} + \frac{Q_{CV}}{T_{ref}}\right) \quad (4)$$

4. EXERGY-BALANCE EQUATIONS FOR A GAS TURBINE PLANT

Equation (4) represents the general exergy balance equation which can be used to derive the exergy balance equations for every component in the gas turbine plant. The exergy balance equations for each individual component are given below:

Exergy balance equation of the compressor

$$W_{C} = \left(E_1^{T} - E_2^{T}\right) + \left(E_1^{M} - E_2^{M}\right) + T_1\left(S_1 - S_2\right) \quad (5)$$

Exergy balance equation of the air pre-heater

$$0 = \left(E_2^{T} - E_3^{T} + E_6^{T} - E_7^{T}\right) + \left(E_2^{P} - E_3^{P} + E_6^{P} - E_7^{P}\right) + T_1\left(S_2 - S_3 + S_6 - S_7 + \frac{Q_{AH}}{T_1}\right) \quad (6)$$

Exergy balance equation of the combustion chamber

$$0 = E^{Ch} + \left(E_3^{T} + E_f^{T} - E_5^{T}\right) + \left(E_3^{M} + E_f^{M} - E_5^{M}\right) + T_o\left(S_3 + S_f - S_5 + \frac{Q_{CC}}{T_o}\right) \quad (7)$$

Exergy balance equation of the turbine

$$W_{T} = \left(E_5^{T} - E_6^{T}\right) + \left(E_5^{M} - E_6^{M}\right) + T_1\left(S_5 - S_6\right) \quad (8)$$

5. RESULTS AND DISCUSSIONS

Chemical, thermal and mechanical exergy flow rates and entropy flow rates at a range of supposed points in the system are described in Table 1. At different points, properties like pressure, temperature, and mass flow rate were quantified and then these values were used to compute these flow rates. Rashidi, [19] proposes that suitable polynomials are placed as the thermo-physical figures in the JANAF tables which enable the attainment of different incoming and outgoing exergies of each system component for analysis [20].

Refer to Table 2 to view the net flow rates of the different exergies passing the limit of each component in the gas-turbine plant at rated circumstances along with the exergy destruction in each component. Exergy flow rate of products are specified by positive values whereas negative values stand for the exergy flow rate of resources or fuel. This is because of the relation between the product of a component and the exergy supplied and between the resource and the used up exergy [21, 22]. For each component and for the whole plant, the exergy flow rates of products, resources and destruction add to give off the value of zero. This zero signifies that the exergy of a system was completely balanced.

Table 1. Property values and thermal, mechanical and chemical exergy flow and entropy production rates at various state points in the gas turbine at rate conditions

State	temperature (K)	Pressure (bar)	Mass flow rate (kg/s)	E^{Ch} (MW)	E^{T} (MW)	E^{M} (MW)	S (MW/K)
1	298.03	1.013	505	0	0	0	0
2	590.7	10.90	505	0	49.33	135.76	0.063
3	800.1	10.90	505	0	117.19	130.99	0.221
4	329.7	22.00	9.9	658.43	0	9.84	-0.0205
5	1425	10.62	514.9	0	386.73	134.38	0.598
6	890.7	1.088	514.9	0	179.29	6.46	0.626
7	704.65	1.044	514.9	0	95.74	2.13	0.501

Table 2. Net exergy flow rates and exergy destruction in the gas turbine power plant at rated condition

Component	E^{W} (MW)	E^{Ch} (MW)	E^{T} (MW)	E^{M} (MW)	E_D (MW)
Compressor	-211.77	0	71.07	133.76	18.32
Air heater	0	0	-8.87	-7.65	11.28
Combustion chamber	0	-568.58	327.39	-8.13	382.41
Gas turbine	370.87	0	-238.24	-128.94	19.73
Total plant	159.1	-568.58	151.35	-10.96	431.74

Figure 3 shows the shift of exergy efficiencies of system components of gas turbine at ambient temperature. For compressor, exergy efficiency decreased from 83.80 to 79.60 whereas for combustion chamber it fell from 48.60 to 45.43. Also, the exergy efficiency of turbine experienced a decline from 73.3 to 68.40. Moreover, it was found that the total irreversibility rate of the plant augmented from 415 to 421 MW approximately while the rational efficiency went through a reduction from 16.53% to 15.44%. Furthermore, total irreversibility rate goes up to 0.43 MW and the rational efficiency of the plant falls up to 0.3% when ambient temperature is increased for 1°C.

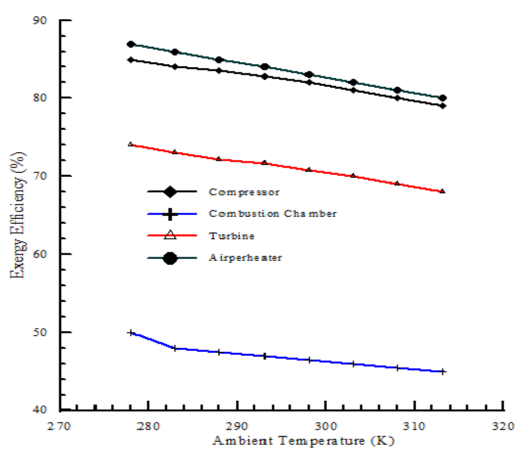

Figure 3. Effect of the ambient temperature on the exergy efficiency of the components of the gas turbine

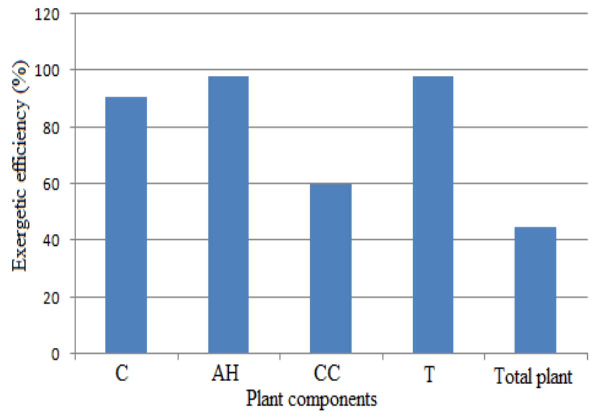

Figure 4. Exergetic efficiency of components and of total plant in the system

The exergetic efficiency η_b of components of the gas-turbine plant can be seen in Figure 4. The figure also demonstrates the exergetic efficiency of the entire plant which is found to be 39%. The findings propose that the exergetic efficiency of all other plant components is much greater than that of the combustion chamber. This is because combustion chamber has high irreversibility. According to Figure 5, the highest magnitude of destruction of total inlet exergy into the plant was observed for the combustion chamber than any other plant components. Moreover, it can be deduced from the figure that the inlet exergy exterminated in the plant was about 60.97% of the whole.

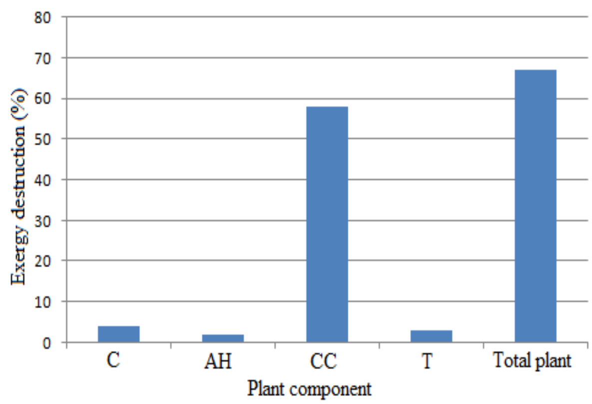

Figure 5. Exergy destruction in components and in total plant in the system

Calculations were done to find out how the exergetic efficiency of components of a plant changes when the turbine inlet temperature is altered. Figure 6 represents the effect of a 120% increase in the turbine inlet temperature on the exergetic efficiency of components. When TIT rises, a slight increment was observed in the exergetic efficiency of turbine whereas no change occurred in exergetic efficiency of air compressor. Also, as observed in Figure 6, the increase in the exergetic efficiency of the combustion chamber was of not noteworthy. According to Figure 7, when the TIT experiences a 120% increment, the functioning of the air compressor remains unaffected whereas the total exergy destruction in the combustion chamber shows a huge decline. Exergy destruction in the air pre-heater amplifies, however the total exergy destruction of the plant reduces up to 23.7%. This is due to the preponderance of the irreversibility in the combustion chamber.

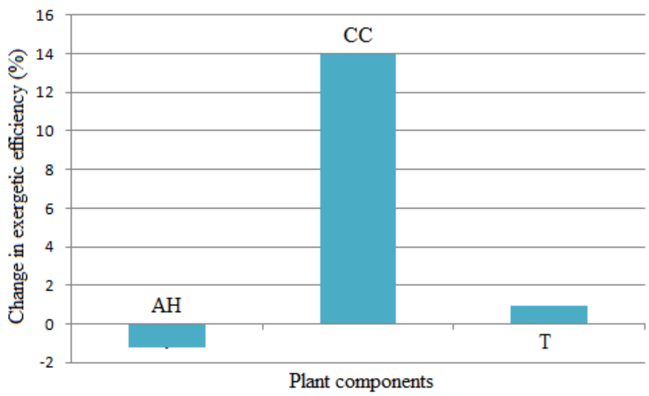

Figure 6. Change in exergetic efficiency of components due to 120% increase in the turbine inlet temperature

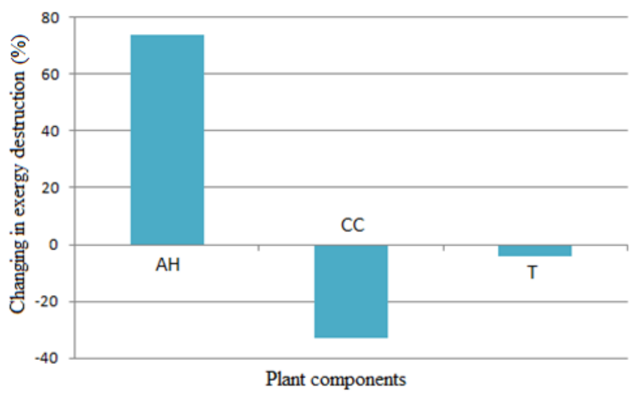

Figure 7. Change in exergy destruction in components due to 120% increase in the turbine inlet temperature

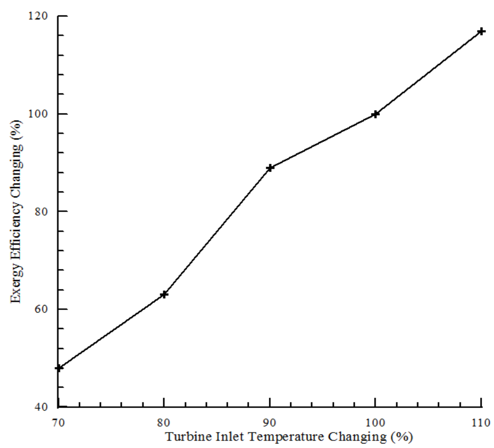

Figure 8. Effect on plant exergetic efficiency of a change in the turbine inlet temperature

Figure 8 and 9 illustrate how the exergetic efficiency of the plant is affected and describe the exergy destruction of a change in the TIT. It can be observed that as the TIT increases, the plant's exergetic efficiency increases simultaneously. On the other hand, with a boost in TIT, the total exergy destruction in the plant decreases, as depicted in Figure 9.

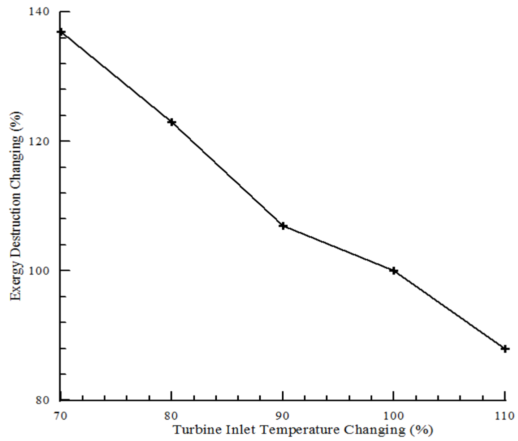

Figure 9. Effect on plant exergy destruction of a change in the turbine inlet temperature

5. CONCLUSIONS

Implementation of an exergy balance to a system or a plant enables us to determine the total consumption (irreversible loss) of usable work potential or exergy provided as the input to the system under study. The inefficiency of any system can be quantitatively measured with the help of this loss of exergy or irreversibility. The analysis includes the study of the impact of the inlet temperature of the turbine on the exergetic competence and on the exergy destruction in gas-turbine system of 159-MW capacity. The research verified that this factor greatly influences the exergetic efficiency and exergy destruction in the combustion chamber. Since the exergy destruction taking place in the combustion chamber is the only significant one, thus the inlet temperature of turbine has an impact on both the exergetic efficiency and the exergy destruction in the plant.

NOMENCLATURE

AFR	Air-fuel ratio
E	Rate of exergy flow (kW)
C_p	Specific heat (kJ/kg.K)
DT	Destruction of total inlet exergy into plant
GT	Gas turbine
m	Mass flow rate (kg/s)
p	Pressure (bar)
Q	Heat transfer rate
R	Universal constant (kJ/kg.K)
S	Entropy flow rate (kW/K)
T	Temperature (K)
TIT	Turbine inlet temperature (K)
T_1	Ambient temperature (K)
W	Power (kW)

Greek symbols

η_e	Exergy efficiency

Subscripts

AH	Air heater
C	Compressor
CC	Combustion chamber
CV	Control volume
D	Destruction
F	Fuel
ref	Standard state
1, 2,....	States number

Superscripts

m	Material
Ch	Chemical
M	Mechanical
T	Thermal
W	Work or electricity

REFERENCES

[1] Y.A.Cengel, and M.A. Boles, "Thermodynamics - An Engineering Approach" 7th edition, New York: McGraw Hill, (2011).

[2] J.B. Jones, and R.E. Dugan, "Engineering Thermodynamics" Upper Saddle River: Prentice-Hall, (1996).

[3] M.J. Moran, and H.N. Shapiro, "Fundamentals of Engineering Thermodynamics" 6th edition, Hoboken, NJ: Wiley, (2008).

[4] I.H. Aljundi, Energy and exergy analysis of a steam power plant in Jordan. Appl. Therm. Eng., 29(2–3), 324-328, (2009).

[5] G. Flavio, A. Segio, A.N. Silvia, Thermoeconomic evaluation of a gas turbine cogeneration system" Energ. Convers. Manage, 41(11), 1191-1200, (2000).

[6] B. Yang, L. Chen, F. Sun, Exergoeconomic performance optimization of an endoreversible intercooled regenerative Brayton combined heat and power plant coupled to variable-temperature heat reservoirs. Int. J. Energy Environ., 3(4), 505-520, (2012).

[7] L. Chen, X. Kan, F. Wu, F. Sun, Finite time exergoeconomic performance optimization of a thermoacoustic cooler with a complex heat transfer exponent. Int. J. Energy Environ., 3(1), 19-32, (2012).

[8] C.P. Du Rand, G. Van Schoor, Fault diagnosis of generation IV nuclear HTGR components – Part I: The error enthalpy–entropy graph approach. Ann. of Nucl. Energy, 40(1), 14-24, (2012).

[9] S.Jegadheeswaran, S.D. Pohekar, Energy and exergy analysis of particle dispersed latent heat storage system. Int. J. Energy Environ., 1(3), 445-458, (2010).

[10] M. Sharma, Varun, Performance estimation of artificially roughened solar air heater duct provided with continuous ribs. Int. J. Energy Environ., 1(5), 897-910, (2010).

[11] R. Selbaş, H. Yazici, A. Şencan, Thermoeconomic optimization of the steam power plant. Int. J. Energy Environ., 1(3), 479-486, (2010).

[12] M. Ghazikhani, M. Ahmadzadehtalatapeh, Experimental investigation of exergy destruction in a 8-kW power plant. Int. J. Energy Environ., 1(5), 815-822, (2010).

[13] P. Regulagadda, I. Dincer, G.F. Naterer, Exergy analysis of a thermal power plant with measured boiler and turbine losses. Appl. Therm. Eng., 30(8–9), 970-976, (2010).

[14] C. Bang-Møller, M. Rokni, B. Elmegaard, Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system. Energy, 36(8), 4740-4752, (2011).

[15] V. Verda, G. Baccino, Thermoeconomic approach for the analysis of control system of energy plants. Energy, 41(1), 38-47, (2012).

[16] S. Oh, H. Pang, S. Kim, H. Kwak, Exergy analysis for a gas-turbine cogeneration system. J Eng Gas Turb Power, 118(4), 782-791, (1996).

[17] E. Cortés, W. Rivera, Exergetic and exergoeconomic optimization of a cogeneration pulp and paper mill plant including the use of a heat transformer. Energy, 35(3), 1289-1299, (2010).

[18] T.J. Kotas, "The Exergy Method in Thermal Plant Analysis" Reprint edition, Malabar, Krieger, (1995).

[19] M. Rashidi, Calculation of equilibrium composition in combustion products. Appl. Therm. Eng., 18(3–4), 103-109, (1998).

[20] JANAF, "Joint Army-Naval-Air Force Thermochemical Tables" NSRDS-N3537, Washington DC, National Bureau of Standard Publications, (1971).

[21] H. Kwak, D. Kim, J. Jeon, Exergetic and thermoeconomic analysis of power plants. Energy, 28(4), 343-360, (2003).

[22] X. Kan, L. Chen, F. Sun, F. Wu, Finite time exergoeconomic performance optimization of a thermoacoustic heat engine. Int. J. Energy Environ., 2(1), 85-98, (2011).