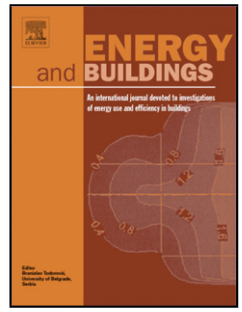
Accepted Manuscript



Title: Advanced exergy analysis of a trigeneration system with a diesel-gas engine operating in a refrigerator plant building

Author: EminAçıkkalp Haydar Aras Arif Hepbasli

PII: S0378-7788(14)00433-2
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2014.05.029
Reference: ENB 5065

To appear in: *ENB*

Received date: 9-3-2014
Revised date: 22-5-2014
Accepted date: 23-5-2014

HIGHLIGHTS (Açıkkalp et al., Energy and Buildings)

►Analyzing a trigeneration system for a plant building with advanced exergy method► Investigating exergy destruction rates comprehensively ►Giving a high priority improvement to Turbo Air Compressor ► Deducting inefficiencies of the system components for possible improvements.

Advanced exergy analysis of a trigeneration system with a diesel-gas engine operating in a refrigerator plant building

EminAçıkkalp[a*], HaydarAras[b], and Arif Hepbasli[c]

[a]*Department of Mechanical and Manufacturing Engineering, Engineering Faculty, Bilecik S.E. University, Bilecik, Turkey*

[b]*Department of Mechanical Engineering, Engineering and Architecture Faculty, Eskisehir Osmangazi University, Eskisehir, Turkey*

[c]*Department of Energy Systems Engineering, Engineering Faculty, Yasar University, Izmir, Turkey*

ABSTRACT

In this paper, a trigeneration system is analyzed using an advanced exergy analysis. The trigeneration system is located in the Eskisehir Industry Estate Zone at Turkey. The exergy efficiency of the system was found to be 0.354, while the total exergy destruction of the system was 16.695 MW. The purpose of this study is to determine the improvement potential of the system. The exergy destruction within the components of the facility is divided into four parts: endogenous, exogenous, avoidable and unavoidable exergy destruction. The components of the trigeneration system have strong relationships with each othersince the endogenous exergy destruction of the components is smaller than the exogenous exergy destruction. The avoidable exergy destruction rates are generally greater than the unavoidable ones. Thus, the trigeneration system possesses a high potential for improvement. This analysis indicates that from a thermodynamic perspective, the TAC (Turbo Air Compressor) is

[*]Correspondence to: Emin Acikkalp, Department of Mechanical and Manufacturing Engineering, Engineering Faculty, Bilecik S.E. University, Bilecik, Turkey.

E-mails: eacikkalp@gmail.com, emin.acikkalp@bilecik.edu.tr

Tel: +90 (228) 2160061

Fax:+90 (228) 216 05 88

the most important component in the system. Through the advanced exergy analysis, information about the relationships among the system components as well as the potential for further improvements may be provided in more detail.

Keywords: exergy analysis, advanced exergetic analysis, exergy destruction, trigeneration system.

Nomenclature

$\dot{E}$	: exergy rate (MW)
$\dot{m}$	: mass flow rate (kg/s)
P	: pressure (kPa)
T	: temperature (K)
y	: exergy destruction ratio

Abbreviations

AC	: air compressor
ACH	: absorption chiller
CAC	: compressed air cooler
E	: engine
G	: generator
HRSG	: heat recovery steam generator
JWC	: jacket water cooler
JWH	: jacket water heater
LOC	: lubrication oil cooler
LOH	: low pressure steam generator
LTC	: low temperature cooler

PEC	: purchased equipment cost ($)
T	: turbine
TAC	: turbo air compressor

Subscripts

D	: destruction
F	: fuel
k	: *k*th component
L	: loss
P	: product

Superscripts

AV	: available
EN	: endogenous
EX	: exogenous
UN	: unavoidable

Greek letters

η	: isentropic/energetic efficiency (%)
ϕ	: exergetic efficiency (%)

1. Introduction

The world's energy demandshave been increasing dramatically over the past decade. Despite the increasing energy demand, environmental issues have gained importance, due to the harmful effects of global warming and the burning of fossil fuels. Therefore, improving the efficiency of power plants and investigating more efficient energy conversion systems has become a priority. The efficiency of conventional power plants based on single prime movers is usually less than 39% [1]. Thus, most of the energy is lost as waste heat. Integrating cooling and heating subsystems into a conventional plant could increase the plant's overall efficiency to 80% [1-3]. Trigeneration is a system used to produce power, heating and cooling using a primary energy source. Trigeneration can be described as a special type of the CHP (combined heat and power) systems that provide heat and power using a primary energy source. In a trigeneration plant, the waste energy from a generation unit, such as a gas turbine, is used to drive both the heating and cooling systems. Therefore, the use of a trigeneration plant results in an improvement of the total efficiency and a reduction of the contamination to the environment.

As it is known, buildings have great ratio in the total energy consumption. Therefore, integrating trigeneration systems to buildings are interoperated as reasonable solutions. Furthermore, exergy based analyses should be performed to use resources efficiently and to protect environment in the buildings. For this reason, researches have started conducting various exergetic, exergoeconomic and exergoenvironmental studies about trigeneration systems in the buildings. Some research examples can be arranged as follows: Santo investigated energy and exergy efficiencies of atrigeneration system using at a building under two different operation strategies [4]. Basrawi et al. realized a theoretical evaluation by using micro co/trigeneration system in a tropic region [5]. Lozano et al.[6] analyzed a trigeneration system installed in a building economically. A trigeneration system was evaluated by integratedcascade refrigerators for supermarkets [7].Coskun et al. [8,9] proposed new thermodynamic parameters for evaluating the performance of geothermal district heating systems.

Each energy conversion system must be analyzed to determine the inefficiencies in the system. Conventional exergy-based analyses are powerful tools that are used to determine such inefficiencies. Exergy is the maximum work that is obtained from the system. However, conventional exergy-based analyses only provide information on theinefficiencies (irreversibilities) and merelyprovide an indicationof the quality of energy use; these analyses do not provide information about the relationships among the system components, i.e.,they cannot define the potential for improvement. To resolve the deficiencies in the conventional exergy analysis, a thermodynamic analysis method called advanced exergy analysis was developed. There are only limited number of papers in the literature related to such advanced exergy-based analyses of power generating systems [10-23]. In Ref. [10], the avoidable/unavoidable exergy destruction concepts were defined firstly. In Ref. [11], exergy destructions of a combined power cycle were divided into avoidable/unavoidable parts.Tsatsaronis explained advanced exergy - based analyses in detail[12]. Endogenous and exogenous exergy methods were presented detailed in [13]. In [14,15], advanced exergy analysis were applied to simple gas turbine cycles. Advanced exergy based analyses were used in liquid natural gas and electricity generation facilities in the studies reported in the references [16] and [17]. Asupercritical power plant was evaluated with advanced exergy methods in Ref. [18]. Conventional and advanced exergy analyses were applied to combined power cycle and results were compared [19]. New methods to assess the thermal systems in terms of environmental and economic ways were investigated in detail [20,21]. In Refs. [22,23], a geothermal district heating system was evaluated as advanced exergy and exergoeconomic analyses.

In this paper, a trigeneration system in a refrigeration plant building was investigated according to an advanced exergy analysis. Thus, the real improvement potential of the system and the relationships among the components were determined in detail, and suggestions were made to improve the performance of the system.

2. System description

The trigeneration system is shown in Fig. 1. This system is located in the Eskişehir Industry Estate Zone in Turkey. The trigeneration system is composed of an engine (E), a turbine (T), an air compressor (AC), a compressed air cooler (CAC), a heat recovery steam generator (HRSG), a lubrication oil heater (LOH), a lubrication oil cooler (LOC), a low temperature cooler (LTC), a jacket water heater (JWH), a jacket water cooler (JWC), an absorption chiller (ACH) and a generator (G). The engine, which is the primary mover of the system, is a duel fuel engine that operates on a combination of the Diesel and Otto cycles, but the engine is more closely to be considered as a Diesel cycle engine. The engine uses pilot fuel to initiate combustion and then operates on natural gas. The trigeneration system generates approximately 5900 kW of electricity, 4300 kW of which is in the form of heat energy that is used to meet the demands of the factory, and 600 kW of which is cooling energy.

The combustion equations of the diesel fuel and the natural gas can be expressed as equations 1 and 2,respectively [24, 25]:

$0.000216\ C_{14.09}H_{24.78} + 0.495522\ (0.7748\ N_2 + 0.2059\ O_2 + 0.0003\ CO_2 + 0.019\ H_2O)$

$\longrightarrow\ 0.003172CO_2+0.012073H_2O+0.097676O_2+0.383931N_2$ (1)

$0.0021816\ (0.9334\ CH_4 + 0.00211\ C_2H_6 + 0.00029\ C_3H_8 + 0.00012\ C_4H_{10} + 0.06408\ N_2) + 0.383931\ N_2 + 0.097676\ O_2 + 0.003172\ CO_2 + 0.012073\ H_2O \longrightarrow 0.023656CO_2 + 0.052975H_2O+0.056741O_2+0.385329N_2$(2)

The specific heats of the combustion gas and the air can be calculated using equations 3 and 4,respectively [24, 25]:

$$c_{P,gas}(T) = 0.93750 + \frac{0.01215}{10^2}T + \frac{0.01670}{10^5}T^2 - \frac{0.07164}{10^9}T^3 \quad (3)$$

$$c_{P,air}(T) = 1.04841 - 0.000383719T + \frac{9.45378}{10^7}T^2 - \frac{5.49031}{10^{10}}T^3 + \frac{7.92981}{10^{14}}T^4 \quad (4)$$

The lower heating values of the natural gas and the diesel fuel were 44661 kJ/kg and 42640 kJ/kg, while the gas constants of the combustion gas and airwere 0.29453 kJ/kgK and 0.2987 kJ/kgK, respectively [22, 23]. The specific exergy of the natural gas (C_aH_b) was calculated as follows [26]:

$$\frac{e_{ch,F}}{LHV} = \lambda_F = 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \quad (5)$$

where λ_F is 1.0308. The fixed parameters of the system are listed in Table 1.

3. Thermodynamic analysis

3.1. Conventional exergy analysis

A conventional exergy analysis must be applied before the advanced exergy analysis can be performed. As mentioned earlier, the exergy analysis reveals the irreversibilities in the system and the quality and amount of an energy resource. Exergy is not conserved, and the relationship between the exergy parameters can be expressed as follows [27]:

$$\dot{E}_D = \dot{E}_F - \dot{E}_P \quad (6)$$

where $\dot{E}_F$, $\dot{E}_P$ and $\dot{E}_D$ represent the fuel exergy rate, the relations product exergy and the exergy destruction rate, respectively.

The exergetic efficiency is [27]

$$\phi = \frac{\dot{E}_F}{\dot{E}_P} \text{ or } \phi = 1 - \frac{\dot{E}_D + \dot{E}_L}{\dot{E}_F} \quad (7)$$

The exergy destruction ratio is [27]

$$y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \quad (8)$$

For the overall system [27],

$$\dot{E}_{F,tot} = \dot{E}_P + \sum_k \dot{E}_{D,k} + \dot{E}_L \quad (9)$$

Here, $\dot{E}_L$ is the rate of the exergy loss of the system. The properties at various locations and the results of the conventional exergy analysis of the system are listed in Table 2 and Table 3, respectively.

3.2 Advanced exergetic and exergoeconomic analyses

In the advanced exergy analysis, the exergy destructions calculated using the conventional exergy analysis can be divided into four basic parts: unavoidable exergy destruction, avoidable exergy destruction, endogenous energy destruction and exogenous exergy destruction. The unavoidable and avoidable exergy destructions can be further split into the endogenous and exogenous exergy destructions.Fig. 2 shows how the exergy destruction is divided into parts. Finally, the mexogenousexergy destruction is calculated to define which components affect other components and to define the nature of these effects. Theavoidable exergy destruction rates ($\dot{E}_{D,k}^{AV}$) indicates the potential for improvement of the components, and the unavoidable exergy destruction rate ($\dot{E}_{D,k}^{UN}$) indicates the inefficiencies in the components that cannot be improved due technical and economic constraints [10].

The unavoidable and avoidable exergy destruction rates are defined by Eqs.(10) and (11),respectively [28]:

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN} \quad (10)$$

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN} \quad (11)$$

To calculate the unavoidable exergy destruction, each component is considered to be isolated and separated from the system. The ratio of the exergy destruction per unit of product exergy $\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN}$ is calculated assuming operation with a high efficiency and low losses [10, 28]. The destruction of endogenous ($\dot{E}_D^{EN}$) and exogenous ($\dot{E}_D^{EX}$) exergyindicate the relationships between the components of the system. The endogenous part of the exergy destruction is associated only with the irreversibilities occurring within the *k*'th component when the following two conditions are simultaneously fulfilled:

• All other components operate in an ideal way.

• The component being considered operates with its current efficiency [12, 28].

However, the exogenous exergy destruction is the exergy destruction caused by the other components. The exogenous part of the exergy destruction rate is calculated by subtracting the endogenous exergy destruction rate from the real exergy destruction rate [28]:

$$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k} - \dot{E}_{D,k}^{EN} \quad (12)$$

The exogenous exergy destruction of each component is denoted as ($\dot{E}_{D,k}^{EX,n}$), which represents the effects of the n'th component on the irreversibilitiesof the k'th component. The difference between the sum of all the $\dot{E}_{D,k}^{EX,n}$ terms and the total exogenous exergy destruction rate is denoted as the mexogenousexergy destruction, which reveals the effects of the system on the considered component [28, 29].

$$\dot{E}_{D,k}^{MEX} = \dot{E}_{D,k}^{EX} - \sum_{\substack{r=1 \\ r \neq k}}^{j-1} \dot{E}_{D,k}^{EX,n} \tag{13}$$

The unavoidable endogenous exergy destruction rate ($\dot{E}_{D,k}^{UN,EN}$) and the unavoidable exogenous exergy destruction rate ($\dot{E}_{D,k}^{UN,EX}$) are calculated as follows [28]:

$$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{P,k}^{EN} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN} \tag{14}$$

$$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN} \tag{15}$$

The avoidable endogenous exergy destruction rate ($\dot{E}_{D,k}^{AV,EN}$) and the avoidable exogenous exergy destruction rate ($\dot{E}_{D,k}^{AV,EX}$) are calculated as follows [28]:

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN} \tag{16}$$

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{AV} - \dot{E}_{D,k}^{AV,EN} \tag{17}$$

4. Results and discussion

Investigating the system using the conventional exergy analysis, the exergy destruction rate was found to be maximized in the engine (14.188 MW). The exergy efficiency and total exergy destruction ratio of the system were calculated to be 0.354 and 0.659, respectively.Therefore, the engine must be the focus of improvement.The minimum exergy destruction rate was in the LTC. Similarly, the maximum exergy efficiency was in the LOC, while the minimum efficiency was in the LTC. The exergy destruction rates of the other components, the exergy efficiencies and the exergy destruction rates are listed in Table 3. In addition, breakdowns of the exergy destruction, exergy efficiency, and exergy destruction ratios of the system are shown in Figs. 3, 4, and 5, respectively.

The detailed results of the advanced exergy analysis based on the assumptions are listed in Tables 4, 5 and 6 are described as follows:

For the system components, according to Table 5,the exogenous exergy destruction rates were higher than the exogenous exergyrates of destruction, except for those of the E and the TAC. This result indicates that the system components have strong relationships. In addition, the maximum endogenous exergy destruction was in the E, due to the large chemical irreversibility caused by the combustion process. In Table 5, the negative destruction of exogenous exergy($\dot{E}_{D,k}^{EX}$, $\dot{E}_{D,k}^{AV,EX}$ and $\dot{E}_{D,k}^{UN,EX}$) indicatesthat the exergy destruction within these components can be decreased by increasing the exergy destruction within the other components. The improvement potential of a component is determined by the avoidable destruction of exergy. Similarly, the destruction of unavoidable exergyrepresentsthe unimprovable part of the components resulting from technical and economic limits, as mentioned before. The TAC, CAC, HRSG, LOH, JWH , JWC and LTC have higher avoidable exergy destruction rates than the unavoidableexergy destruction rates according to Table 5 again. This result reveals these components have high potential for improvement. However, the E, LOC and ACH had greater avoidable exergy destruction rates; therefore, these components must be the focus of improvement. The maximum potential for improvement was in the E (1.614 MW), but this value was relatively low becausea large fraction of the exergy destruction was unavoidable (12.574 MW). Examining the avoidable exergy destruction rates of the system (Table 5) reveals that the exogenous parts of the avoidable exergy destruction are higher than the endogenous avoidable exergy destruction parts, except for those from the E, TAC, and ACH. This result indicates that the potential for improvement of a component is generally associated with the other components. It is interesting that the ACH yields negative ($\dot{E}_{D,k}^{AV}$ and $\dot{E}_{D,k}^{AV,EN}$) values in Table 5. The negative $\dot{E}_{D,k}^{AV}$ indicates that the ACH has a larger exergy destruction rate; however, this value can be improved, but the exergetic efficiency will increase. The negative $\dot{E}_{D,k}^{AV,EN}$ indicates that a reduction of the exergy destruction within the ACH can be achieved by decreasing the inlet specific exergy of the component of the air mass flow rate. By applying these methods, the endogenous exergy destruction rate of the E can be reduced; thus, the available endogenous exergy destruction rate can be similarly reduced. As indicated in Table 6, the LTC had negative values for the mexogenousexergy production. This result indicates that the exergy destruction of the trigeneration system must be increased in order to decrease the exergy destruction in the LTC. In addition, the E and the TAC generally have large effects on all the other components.

Figs.6-9 show breakdowns of the advanced exergetic destruction parameters for the entire system. According to Fig.6, the endogenous exergy destruction has the highest rate 96.5%. This high rate proves that the relationships of the system components are very weak for the system. A similar result is shown in Fig.7. The potential for improvement of the exergy destruction cost rates of the entire system was only 18.8%. Moreover, 70.5% of this potential improvement was based on the components themselves (Fig.8). In Fig.9, it is apparent that the unavoidable parts of the exergy destruction rateare endogenous.

The following results are acquired when the considered plant is compared to some systems in the literature [8,9,11-17]: In Ref. [8], the concepts of the avoidable and the unavoidable exergetic parts of a power plant were defined . It is seen that 41% of the total exergy destruction is avoidable. It shows the improvement potential of the system is relatively low. In Ref. [9], a similar research was conducted for combined power plant. According to the results, the avoidable exergy destruction was 33. In Ref. [11], refrigeration and gas turbine systems were investigated for endogenous and exogenous exergy destruction rates. Endogenous part of exergy destruction was 68% for refrigeration system and this means that, the relations of the components at the system are strong. Endogenous exergy destruction part of the gas turbine systemconsists of 69% of the total exergy destruction rate. Relations of components in the gas turbine cycle is strong. In Ref. [12], a simple gas turbine cycle and cogeneration system that operated with different fuels were investigated. For both system, endogenous exergy destruction rates of the system was bigger than exogenous exergy destruction rates. In Ref. [13], advanced exergy analysis was conductedfor simple open gas turbine cycle. It was found that 77% of the exergy destruction rate was endogenous and only 29% of the exergy destruction rate was avoidable. Advanced exergy analysis was applied to a novel system that generates electricity and vaporizing liquefied natural gas was investigated with [14]. Its endogenous exergy destruction rate was 88% ,while its avoidable exergy destruction rate was57%. In Ref. [15], system has 57% improvement potential. In Ref. [16], endogenous exergy rate of the investigated system is 85% and its improvement potential is 8%. In Ref. [17],endogenous exergy rate is 83% and avoidable exergy destruction rate is 33% of the system respectively. Endogenous exergy of the considered system was found to be 96.5 and destruction rates of the systems ranged from 65 to 85% generally. The improvement potentials of the systems in the literature varied from 30-40% while our system had 18.8 % improvement potential.Components relations and improvement potential of our system, were lower by comparing to the ones in the literature.

5. Conclusions

The use of the conventional exergy analysis has the following deficiencies:

- It can lead to misinterpretations that result in the formation of incorrect improvement strategies
- It does not provide useful information regarding the relationships among the components of the system.

In this paper, we have investigated trigeneration system using an advanced exergy analysis method and listed some concluding remarks as follows:

- In an attempt to eliminate these deficiencies stated above, an advanced exergy analysis was used. The E and especially the TAC were determined to be the most important components of the system and therefore must be examined to improve the system.
- The relations of the components were really weak because 96.5 % of the total exergy destruction was endogenous.
- The improvement potential of the system was very low due to the 18.8 % avoidable exergy destruction rate of the system.

As can seen from the results obtained, advanced exergy analysis is more powerful tool in assessing and improving energy-related systemscompared to the conventional exergy analysis. In this regard, it is our recommendation that engineers apply an advanced exergy analysis to energy conversion systems to achieve the correct results and thereby devise the appropriate improvement strategies.

Acknowledgements

The authors are grateful to the company along with the technical staff, located in the Eskişehir Industry Estate Zone, Turkey for the support. They also would like to thank the reviewers for their valuable and constructivecomments, which have been very useful in improving the quality of the paper.

References

[1] F.A Al-Sulaiman, F.Hamdullahpur, I. Dincer,Trigeneration: a comprehensive review based on prime movers, International Journal of Energy Research35(3) (2011) 233-258.

[2] International Energy Agency,Combined heat and power: evaluating the benefits of greater global investment, 2008.

[3] K.Tom, Combined heating and power and emissions trading: options for policy makers. International Energy Agency, July 2008.

[4] D.B.Espirito Santo, Energy and exergy efficiency of a building internal combustion engine trigeneration system under two different operational strategies,Energy and Buildings 53 (2012) 28–38.

[5] F. Basrawi, T. Yamada, S. Obara, Theoretical analysis of performance of a micro gas turbine co/trigeneration system for residential buildings in a tropical region, Energy and Buildings 67 (2013) 108–117.

[6] M.A. Lozano, M.Carvalho, L. M. Serra, Allocation of economic costs in trigeneration systems at variable load conditions, Energy and Buildings 43 (2011) 2869–2881.

[7] M.A. Marimóna, J. Arias, P. Lundqvist, J.C. Bruno, A. Coronas, Integration of trigeneration in an indirect cascade refrigeration system in supermarkets, Energy and Buildings 43 (2011) 1427–1434.

[8] C. Coskun, Z. Oktay, I. Dincer, Modified exergoeconomic modeling of geothermal power plants,Energy 36 (2011) 6358-6366.

[9] C. Coskun, Z. Oktay, I. Dincer, New energy and exergy parameters for geothermal district heating systems,Applied Thermal Engineering 29 (2009) 2235–2242.

[10] G. Tsatsaronis, P. Moung – Ho, On avoidable and unavoidable exergy destructions and investment costs in thermal systems, Energy Conversion and Management 43 (2002) 1259-1270.

[11] F. Cziesla, G.Tsatsaronis, Z. Gao, Avoidable thermodynamic inefficiencies and cost in an externally fired combined cycle power plant, Energy 31 (2006) 1472-1489.

[12] G. Tsatsaronis, Recent developments in exergy analysis and exergoeconomic, International Journal of Exergy 5 (2008) 489 - 499.

[13] S. Kelly, G. Tsatsaronis, T. Morosuk, Advanced exergeticanalysis: approaches for splitting the exergy destruction into endogenous parts, Energy 34 (2009) 384-391.

[14] N. Razmara, R.K. Saray, A simple gas turbine system and co-generation power plant improvement based on endogenous and exogenous exergy destruction, Proceedings Institute of Mechanical Engineering 24 (2009) 433-447.

[15] T. Morosuk, G. Tsatsaronis, Advanced exergy analysis for chemically reaction systems-application to a simple open gas-turbine system, International Journal of Thermodynamics 12 (2009) 105-111.

[16] G. Tsatsaronis, T. Morosuk, Advanced Exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas, Energy 35 (2010) 820-829.

[17] T. Morosuk,, G. Tsatsaronis, A. Boyano, C. Gantiva, Advanced exergy-based analyses applied to a system including lng regasification and electricity generation, International Journal of Energy and Environmental Engineering 3 (2012) 1-9.

[18] L. Wang, Y. Yang, T. Morosuk, G. Tsatsaronis, Advanced thermodynamic analysis and evaluation of a supercritical power plant, Energies 5 (2012) 1850-1863.

[19] F. Petrakopoulou, G. Tsatsaronis, T.Morosuk, A. Carassai, Conventional and advanced exergetic analysis applied to a combined power plant, Energy 41 (2012) 146-152.

[20] F. Petrakopoulou, G. Tsatsaronis, T.Morosuk, C. Paitazoglou, Environmental evaluation of a power plant using conventional and advanced exergy-based methods, Energy 45 (2012) 23-30.

[21] F. Petrakopoulou, G. Tsatsaronis, T.Morosuk, Advanced exergoeconomic analysis applied to a complex energy conversion system, Proceedings of the ASME 2010 International Mechanical

Engineering Congress & Exposition (Imece2010), November 12-18, 2010, Vancouver, British Columbia, Canada.

[22] A. Hepbasli, A. Kecebas, A comparative study on conventional and advanced exergetic analyses ofgeothermal district heating systems based on actual operational data, Energy and Buildings 61 (2013) 193–201.

[23] A.Kecebas，A. Hepbasli, Conventional and advanced exergoeconomic analyses of geothermal district heating systems, Energy and Buildings 69 (2014) 434–441.

[24] O.Balli, Performance assessments of cogenarition systems using the energy, availability (exergy) and exergoeconomic analysis methods , PhD Thesis, Eskisehir OsmangaziUniversity, Eskisehir, Turkey, 2008 (in Turkish).

[25] O.Balli, H.Aras, A. Hepbasli, Thermodynamic and thermoeconomic analyses of a trigeneration (trigen) system with a gas–diesel engine: part II – An Application, Energy Conversion and Management 51 (2010) 12260–2271.

[26] M.J. Moran, H.N. Shapiro, Fundamentals of engineering thermodynamics. NewYork: John Wiley,1995.

[27] A. Bejan, G. Tsatsaronis, M. Moran, Thermal design and optimization. New York: Wiley, 1996.

[28] F.Petrakopoulou, Comparative evaluation of power plants with CO_2 capture: thermodynamic, economic and environmental performance, Ph.D. thesis, Berlin Technical University, Berlin, 2011.

[29] G. Tsatsaronis, T. Morosuk, Advanced exergoeconomic evaluation and its application to compression refrigeration machine, Proceedings of the ASME International Mechanical Engineering Congress and Exposition, 2007, Seattle, USA Cd-Rom, file 2007-41202.

Figure Captions

Fig. 1. Schematic diagram of the system.

Fig. 2. Dividing the exergy destruction (adapted from Ref. [22]).

Fig. 3. Exergy destruction rates of the components in the system.

Fig. 4. Exergy efficiencies of the components in the system.

Fig. 5. Exergy destruction ratios of the components in the system.

Fig. 6. Breakdown of the endogenous and exogenous exergy destruction rates of the system.

Fig. 7. Breakdown of the available and unavoidable exergy destruction rates of the system.

Fig. 8. Breakdown of the available exergydestruction rates of the system.

Fig. 9. Breakdown of the unavoidable exergy destruction rates of the system.

Table Captions

Table 1. Fixed parameters of the trigeneration system.

Table 2. Mass flow rates, pressures, temperatures, energy rates and exergy rates of the trigeneration system.

Table 3. Exergetic parameters of the trigeneration system.

Table 4. Assumptions used in the advanced exergy analysis.

Table 5. Advanced exergy parameters of the system.

Table 6. Mexogenous exergy parameters of the system.

Table 1

Fixed parameters of the trigeneration system.

Parameter	**Unit**	**Value**
$\dot{W}_E$	MW	6.390
$\dot{W}_{AC}$	MW	1.292
$\dot{W}_T$	MW	1.716
η_E	-	0.327
η_{AC}	-	0.771
η_T	-	0.700
COP_{ACH}	-	0.912

Table 2

Mass flow rates, pressures, temperatures, energy rates and exergy rates of the trigeneration system.

Point	Fluid	$\dot{m}$ (kg/s)	T (K)	P (kPa)	$\dot{E}$ (MW)
1	Air	14.75	298.15	101.325	0
2	Air	14.75	402.15	229	1.292
3	Air	14.75	323.15	216	1.009
4	Diesel fuel	0.04	298.15	698	1.808
5	Natural gas	0.4	408.15	33600	18.77
6	Combustion gas	15.19	673.15	225	3.081
7	Combustion gas	15.19	578.15	110	1.365
8	Combustion gas	15.19	398.15	102	0.243
9	Water	28.85	388.15	700	1.393
10	Water	28.85	408.15	685	2.009
11	Lubrication oil	21.93	354.15	550	0.226
12	Lubrication oil	21.93	335.15	550	0.092
13	Lubrication oil	21.93	329.15	550	0.061
14	Water	80.15	368.15	370	2.412
15	Water	80.15	357.15	370	1.753
16	Water	11.26	357.15	370	0.246
17	Water	11.26	325.15	370	0.057
18	Water	80.15	352.15	370	1.513
19	Water	20.21	343.15	350	0.266
20	Water	20.21	348.15	340	0.325

21	Water	20.21	351.15	335	0.361
22	Water	20.21	365.15	319	0.558
23	Water	20.21	362.15	317	0.514
24	Water	18.71	291.25	490	0.013
25	Water	18.71	283.15	475	0.038
26	Water	26.69	302.15	360	0.015
27	Water	26.69	308.15	360	0.025
28	Water	26.69	298.15	360	0.006
29	Water	80.56	298.15	360	0.016
30	Water	80.56	302.15	342	0.015
31	Water	80.56	305.15	325	0.034
32	Water	80.59	301.99	306.3	0.035

Table 3

Exergetic parameters of the trigeneration system.

Component	$\dot{E}_F$ (MW)	$\dot{E}_P$ (MW)	$\dot{E}_D$ (MW)	ϕ	y
E	20.578	6.390	14.188	0.311	0.871
TAC	1.716	1.292	0.424	0.753	0.003
CAC	0.283	0.059	0.224	0.208	0.014
HRSG	1.122	0.616	0.506	0.549	0.031
LOH	0.134	0.036	0.098	0.269	0.006
JWH	0.659	0.197	0.462	0.299	0.028
JWC	0.189	0.019	0.170	0.101	0.010
LOC	0.030	0.002	0.028	0.933	0*
LTC	0.019	0*	0.019	0*	0.001
ACH	0.600	0.024	0.576	0.040	0.035

*****: value assumed to be 0, because it is smaller than 0.001.

Table 4

Assumptions used in the advanced exergy analysis.

Component	Operating Conditions	Theoretical Conditions	Unavoidable Conditions
E	η =0.327	η =1	η =0.38
TAC	η =0.735	η =1	η =0.80
CAC	ΔT_{min} = 54 K	ΔT_{min} = 0	ΔT_{min} =10 K
	$\Delta P = 5\%$	$\Delta P = 0$	$\Delta P = 0$
HRSG	ΔT_{min} = 170 K	ΔT_{min} = 0	ΔT_{min} =10 K
	$\Delta P = 5\%$	$\Delta P = 0$	$\Delta P = 0$
LOH	ΔT_{min} = 3 K	ΔT_{min} = 0	ΔT_{min} =2 K
	$\Delta P = 2\%$	$\Delta P = 0$	$\Delta P = 0$
JWH	ΔT_{min} = 3 K	ΔT_{min} =0	ΔT_{min} = 2 K
	$\Delta P = 5\%$	$\Delta P = 0$	$\Delta P = 0$
JWC	ΔT_{min} = 52 K	ΔT_{min} = 0	ΔT_{min} = 10 K
	$\Delta P = 3\%$	$\Delta P = 0$	$\Delta P = 0$
LOC	ΔT_{min} =27 K	ΔT_{min} = 0	ΔT_{min} = 10 K
	$\Delta P = 0\%$	$\Delta P = 0$	$\Delta P = 0$
LTC	ΔT_{min} = 6 K	ΔT_{min} =0	ΔT_{min} =2 K
	$\Delta P = 3\%$	$\Delta P = 0$	$\Delta P = 0$
ACH	COP= 0.91	COP= 2.49	COP= 1.20

Table 5

Advanced exergy parameters of the system.

Component	$\dot{E}_{D,k}$ (MW)	$\dot{E}_{D}^{EN}$ (MW)	$\dot{E}_{D}^{EX}$ (MW)	$\dot{E}_{D,k}^{AV}$ (MW)	$\dot{E}_{D,k}^{UN}$ (MW)	$\dot{E}_{D,k}^{AV,EN}$ (MW)	$\dot{E}_{D,k}^{AV,EX}$ (MW)	$\dot{E}_{D,k}^{UN,EN}$ (MW)	$\dot{E}_{D,k}^{UN,EX}$ (MW)
E	14.188	14.188	0	1.614	12.574	3.683	-2.069	10.505	2.069
TAC	0.424	1.552	-1.128	0.220	0.204	1.448	-1.228	0.104	0.100
CAC	0.224	0.021	0.203	0.203	0.021	0.020	0.183	0.001	0.020
HRSG	0.506	0.126	0.380	0.455	0.051	0.073	0.382	0.053	-0.002
LOH	0.098	0*	0.098	0.095	0.003	0*	0.095	0*	0.003
JWH	0.462	0.056	0.406	0.450	0.012	0.056	0.394	0*	0.012
JWC	0.170	0.001	0.169	0.131	0.039	-0.019	0.150	0.020	0.019
LOC	0.029	0*	0.029	0.014	0.015	0*	0.014	0*	0.015
LTC	0.019	0*	0.019	0.011	0.008	-0.019	0.030	0.019	-0.011
ACH	0.576	0.171	0.405	-0.055	0.631	0.148	-0.203	0.023	0.608

*: Value assumed to be 0, because it is smaller than 0.001.

Table 6

Mexogenous exergy parameters of the system.

Exogenous exergy destruction of each component (MW)	**Effects of the other components on the exogenous exergy destruction (MW)**
CAC	E -0.018
0.203	TAC 0.087
	MX 0.134
HRSG	E -0.034
0.380	TAC -0.087
	MX 0.501
LOH	E 0*
0.098	TAC 0.016
	CAC 0*
	MX 0.082
JWH	E -0.046
0.406	TAC -0.02

	CAC -0.054
	LOH 0.025
	MX 0.481
JWC	E 0*
0.169	TAC 0.002
	CAC 0*
	JWH 0*
	LOC 0*
	LTC 0*
	MX 0.167
LOC	E 0.001
0.029	TAC 0*
	CAC 0*
	LOH 0*
	JWH 0*
	JWC 0*
	MX 0.028

LTC	E 0.093
0.019	TAC 0.027
	CAC 0.124
	LOH 0.017
	JWH 0.007
	JWC 0.007
	MX -0.256
ACH	E 0.049
0.405	TAC 0.039
	JWH -0.110
	CAC -0.091
	LOH -0.090
	MX 0.608

*: Value assumed to be 0, because it is smaller than 0.001.

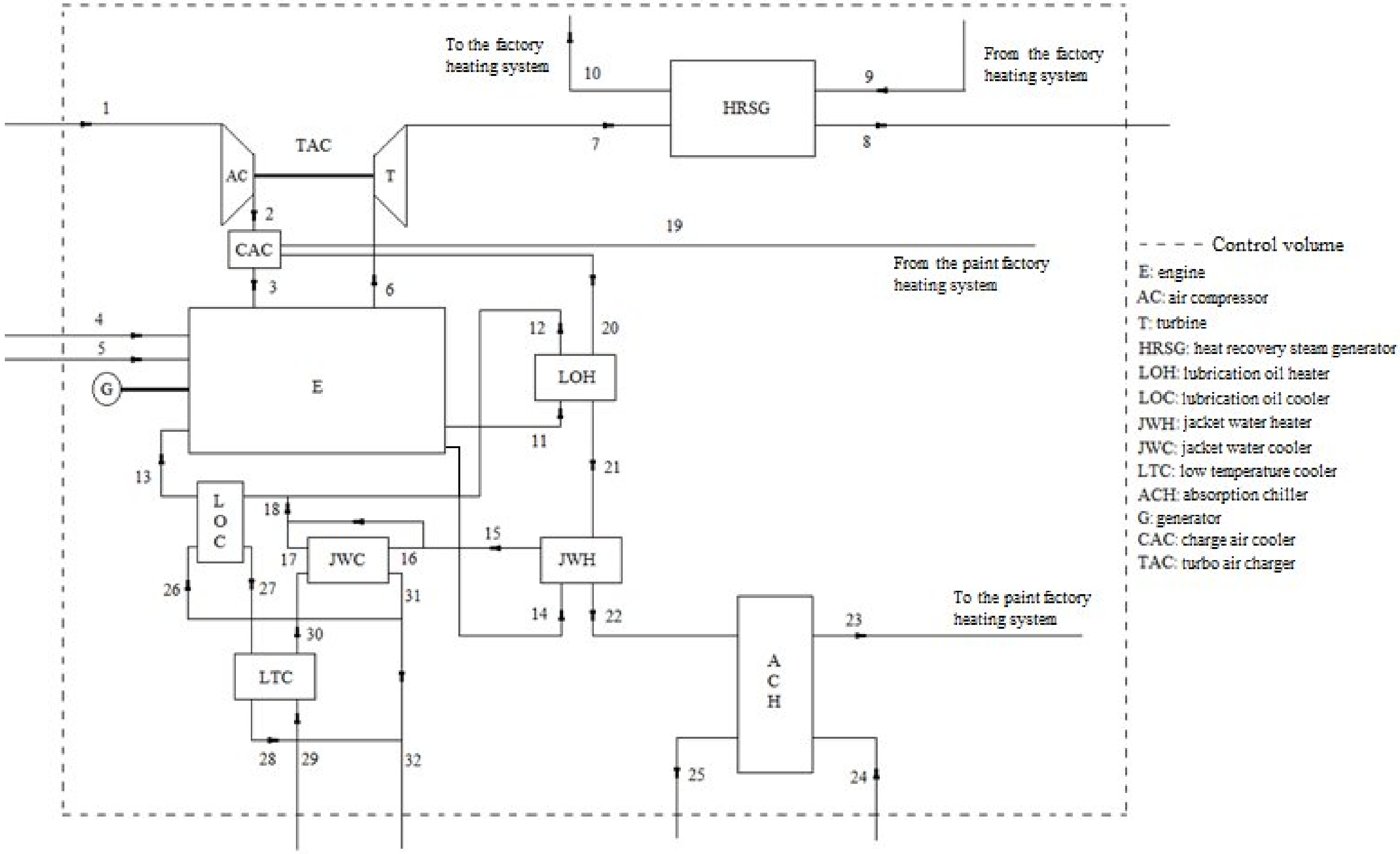


Fig. 1. Schematic diagram of the system.

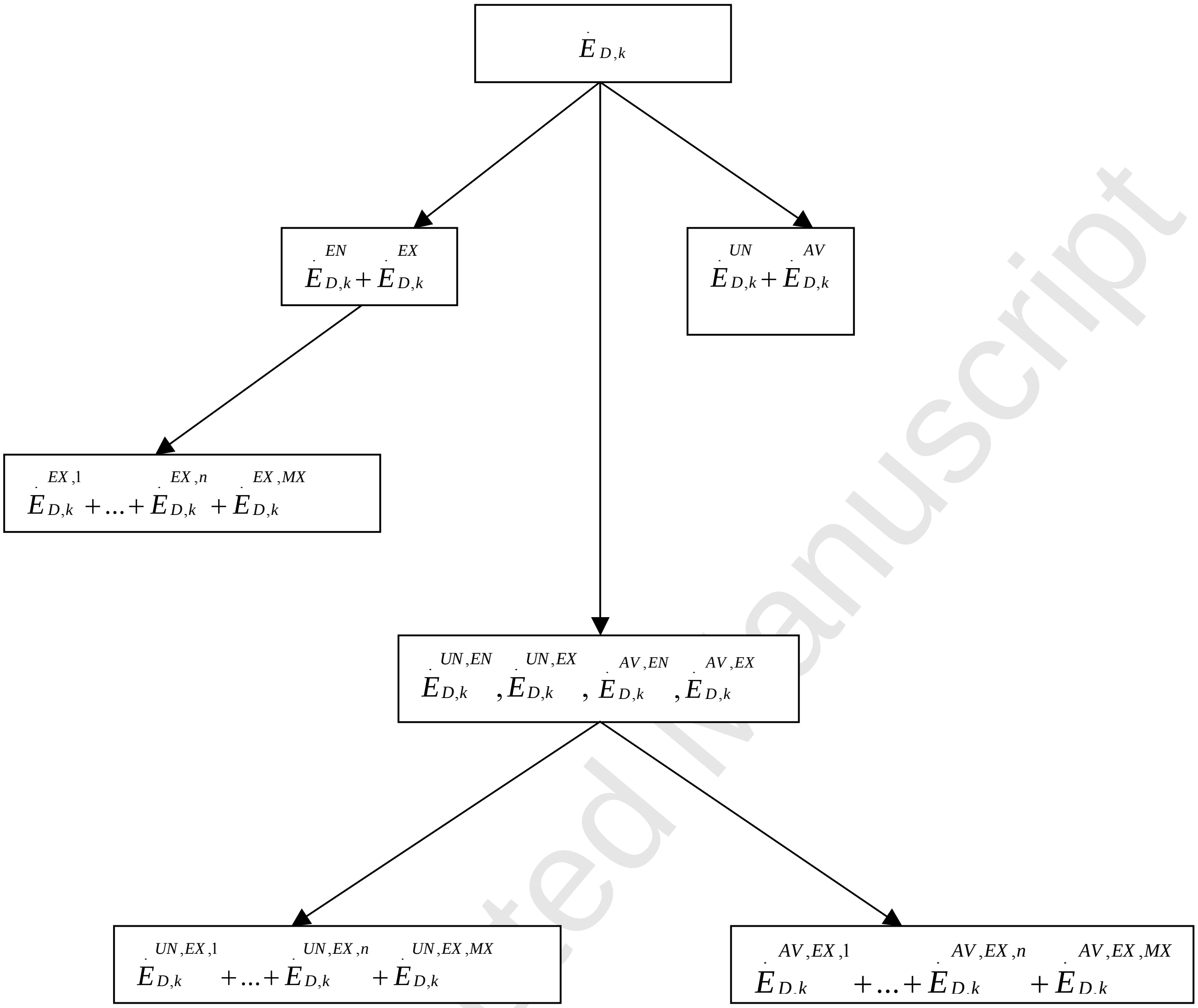


Fig. 2. Dividing the exergy destruction (adapted from Ref. [22]).

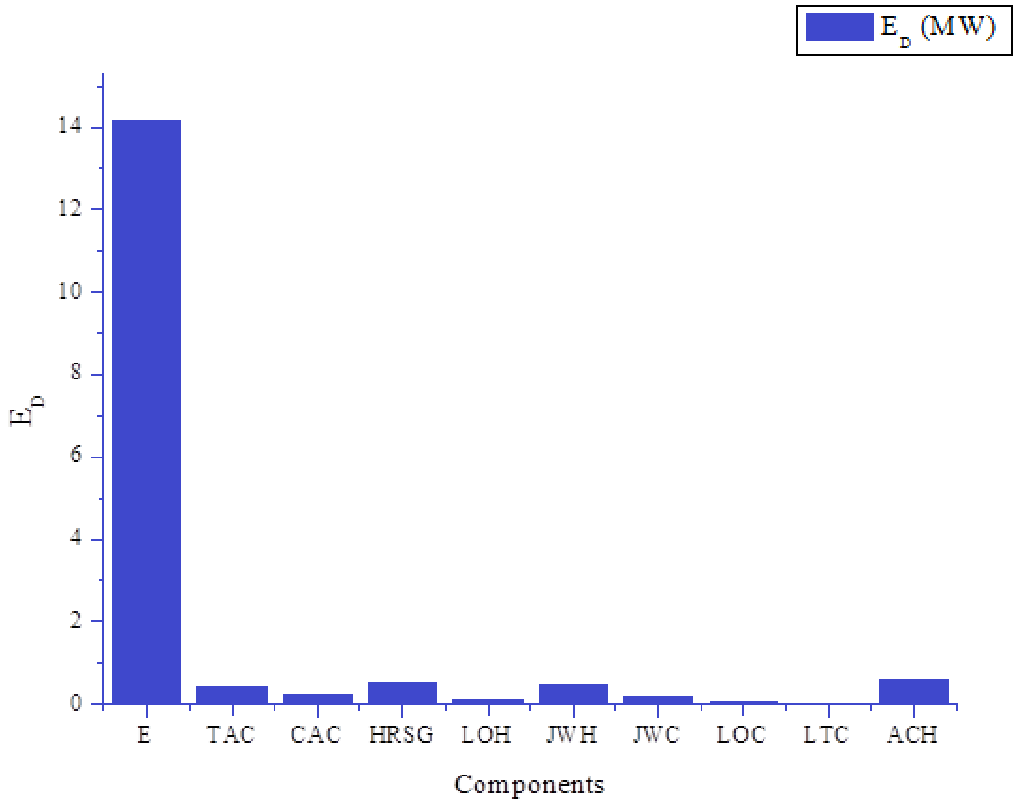


Fig. 3. Exergy destruction rates of the components in the system.

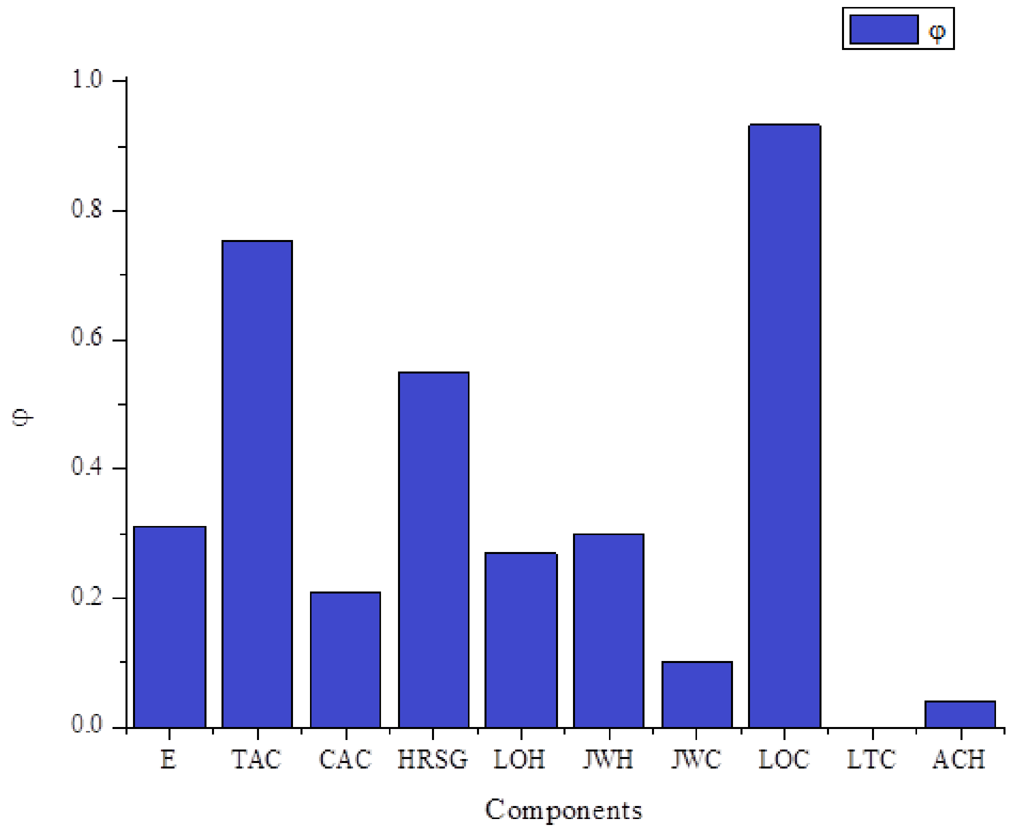


Fig. 4. Exergy efficiencies of the components in the system.

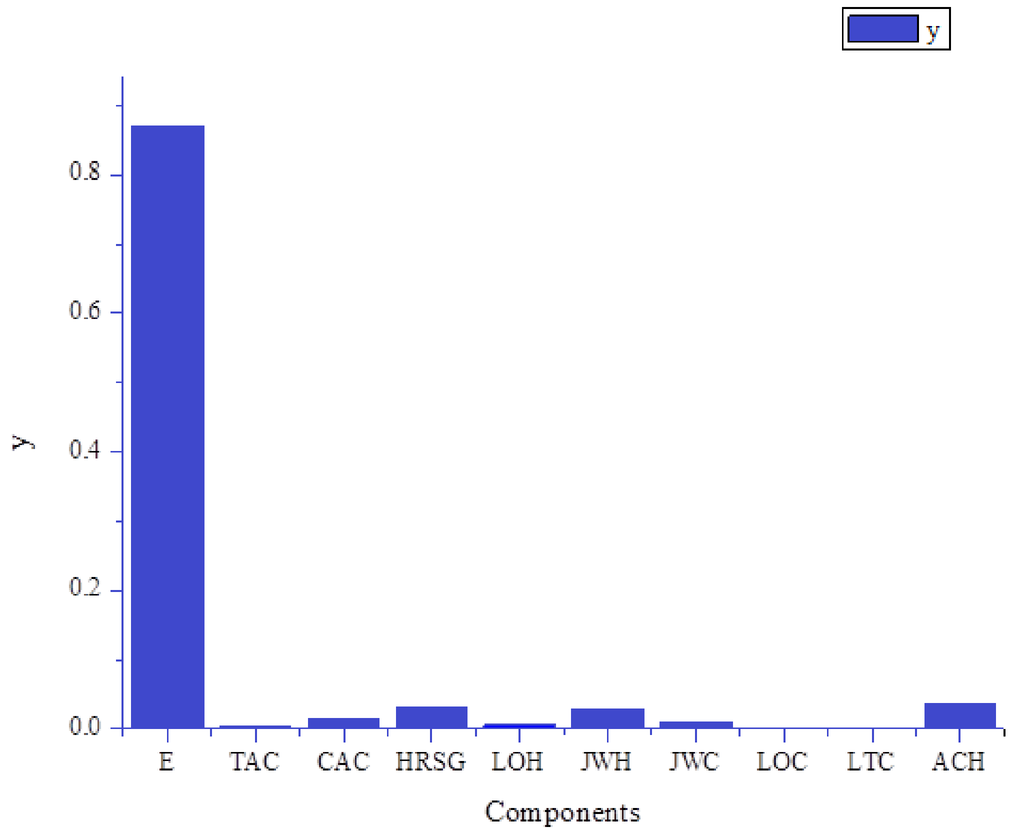


Fig. 5. Exergy destruction ratios of the components in the system.

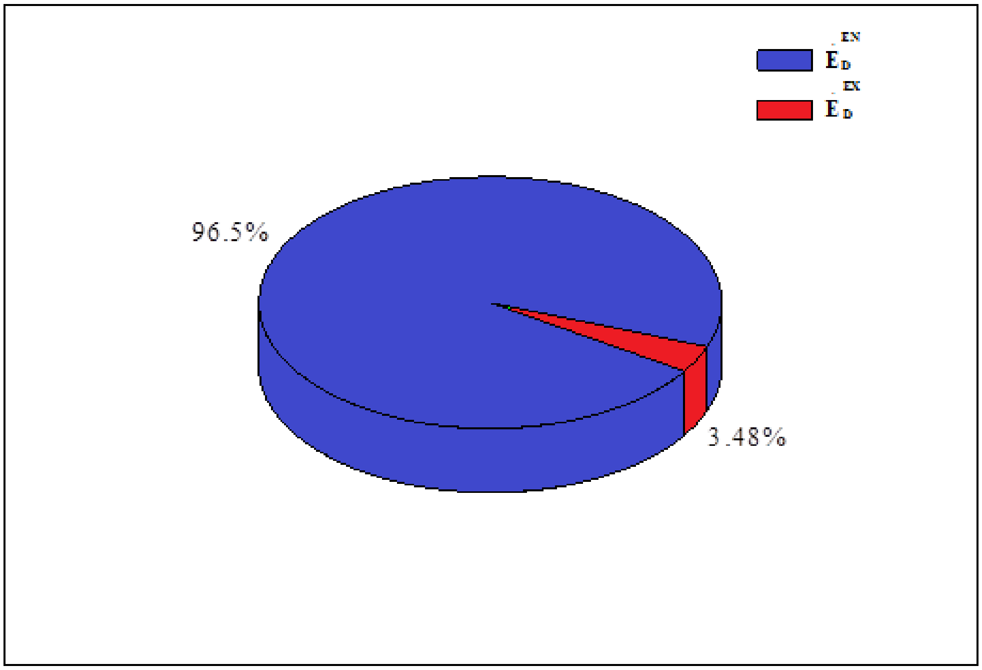


Fig. 6. Breakdown of the endogenous and exogenous exergy destruction rates of the system.

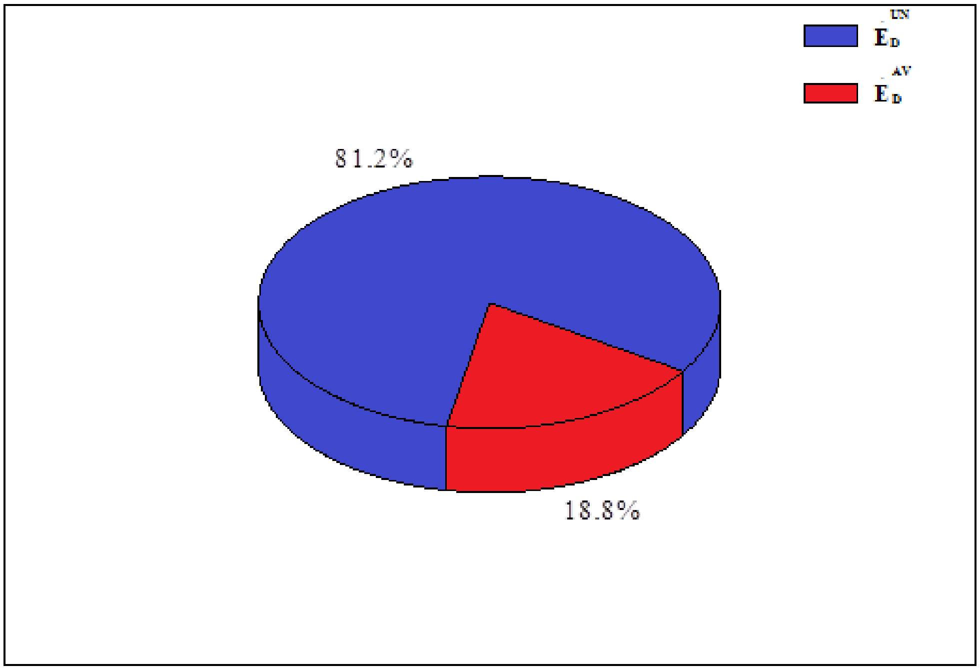


Fig. 7. Breakdown of the available and unavoidable exergy destruction rates of the system.

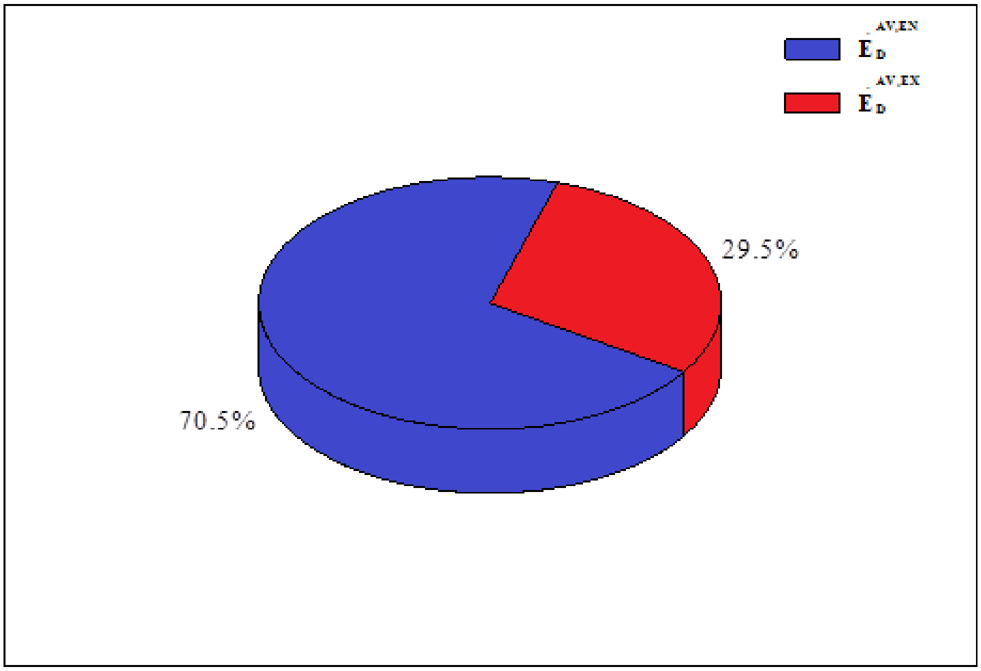


Fig. 8. Breakdown of the available exergy destruction rates of the system.

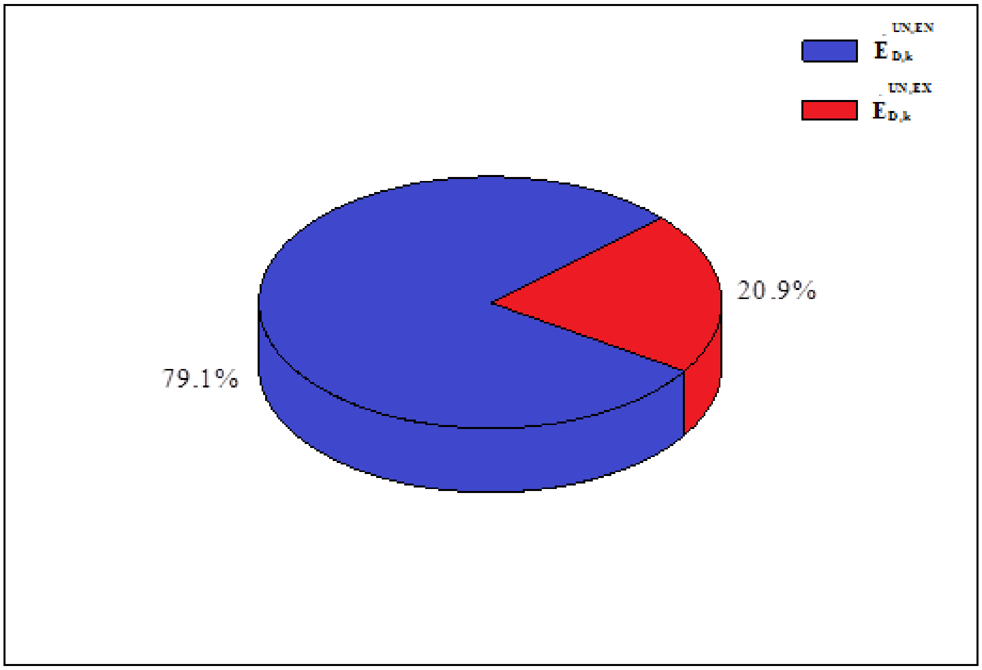


Fig. 9. Breakdown of the unavoidable exergy destruction rates of the system.