Energetic and Exergetic Analysis of
Internal Combustion Engine Cogeneration System

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Abstract

In this article, the first and second law analysis of diesel engine based cogeneration system was performed. Fuel utilization efficiency, rate of power, and rate of process heat of the plant were determined and various efficiencies based on both energy and exergy methods and the performance assessment parameters are defined for both the system components and the entire cogeneration plant. The objectives of this study are to calculate the exergy destruction within the plant and exergy loss to the environment and apply the performance assessment parameters to the components and entire cogeneration plant. The system under survey in this work was a diesel engine based cogeneration system that produces 250 kW of electricity and increases the temperature of water from 80 °C to 120 °C at 2 bar and 1.75 kg/s. The analysis showed that the least efficient component in the system is diesel engine with the exergetic efficiency of 39.31%. Also, fuel utilization efficiency of the overall plant was found to be 90.47% and the exergetic efficiency was 51.08%.

Keywords: Energy, Exergy, Efficiency, Diesel engine, Cogeneration.

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1. Introduction

Developing techniques for designing efficient and cost effective energy systems is one of the foremost challenges that energy engineers face. In a world with finite natural resources and increasing energy demand by developing countries, it becomes increasingly important to understand the mechanisms which degrade energy and resources and to develop systematic approaches for improving the design of energy systems and reducing the impact on the environment [1].

Cogeneration systems have emerged as an effective method of heat conversion due to involvement of both production of electricity and useful thermal energy in one operation. These systems utilize the waste heat produced during electricity generation and allow more efficient fuel consumption. Thus, this system has more economical benefits than production of these two energy forms in separate systems [2]. Since combined heat and power (CHP) systems involve the production of both thermal energy, generally in the form of steam or hot water, and electricity, the efficiency of energy production can be increased from current levels that vary from 35% to 55% in the conventional power plants to over 80% in the combined heat and power systems [3].

There is a range of technologies that can be applied to cogenerate electricity and useful thermal energy. These technologies are generally classified according to their prime movers. Currently available systems include: steam turbines, gas turbines, combined cycles, and reciprocating engines. There are also new technologies which are expected to become economically available in the next years. These include: fuel cells, Stirling engine, and micro turbines [4].

Compact cogenerators can have gas turbines or internal combustion engines as prime movers. Cogeneration with an internal combustion engine consists of the engine itself connected to an electrical generator and also heat exchangers at the water jackets and exhaust gas for heat recovery [5].

Combined heat and power plants with internal combustion engines are widely used because of their cost effectiveness, mobility, and high efficiency. With an increasing number of these units being built; it is of prime importance to verify the effective advantage of using internal combustion engines and the real operation and maintenance costs [6].

One of the major advantages of reciprocating engines is their higher electrical efficiency as compared with other prime movers. The exhaust gases from diesel cogeneration plants represent a significant amount of thermal energy that traditionally has been used for combined heat and power applications. In regions of high ambient temperature it may be more appropriate to utilize the waste heat to facilitate indoor climate control or to improve the performance of the prime generation unit [7].

Compression ignition diesel engine is among the most efficient simple cycle power generation options on the market. These engines may be suitable for the sites where power or processes are cyclical or not continuous and when natural gas is not available or involve high cost. Efficiency levels increase with engine size and range from about 30% for small high speed diesels up to 42–48% for the large bore, slow speed engines [8]. According to the studies presented, diesel engines are more efficient than the equivalent ones with gas turbines since they have a higher electrical performance. The most important parameter is the electricity produced in cogeneration scheme [9].

The second law of thermodynamics complements and enhances an energy analysis as it considers the real thermodynamic inefficiencies in processes or systems. Exergy characterizes the thermodynamic quality of a given quantity of energy [10]. Exergetic efficiency compares the actual performance of a process/system with the ideal one and exergy destruction quantifies the losses that hinder the performance [11]. In the literature, there exist a number of studies that consider energetic and exergetic performances of cogeneration systems. Bilgen [12] presented exergetic and engineering analyses as well as a simulation of gas turbine based cogeneration plants consisting of a gas turbine, heat recovery steam generator, and steam turbine. Khaliq and Kaushik [13] presented the second law approach for the thermodynamic analysis of the reheat combined Brayton/Rankine power cycle. Balli et al. [14] evaluated exergetic performance of a combined cycle CHP system in Turkey. Wang et al. [15] performed exergy analyses for different cogeneration power plants in cement industry. Ameri et al. [16] presented exergy analysis of a 420 MW combined cycle power plant and Ghosh and De [17] performed exergy analysis of a cogeneration plant using coal gasification and solid oxide fuel cell. Also Can et al. [18] presented energetic, exergetic, and economic analyses of a cogeneration thermic power plant in Turkey.

Although power plants and cogeneration systems actuated with internal combustion engines are not a new concept, there have not been many studies on diesel engine actuated ones in literature. Compressed ignition engine cycles are more preferred for power production in marine diesel applications and most of studies have been focused on the thermodynamic and performance analysis of engine itself for conventional automotive research and also thermoeconomic analysis of steam and gas turbines and the environmental impacts of diesel engines [8].

Based on the conditions of energy resources of some Asian and South European countries and fuel to power price structure, diesel engine based power plants and cogeneration have been chosen as the best power producing scheme for some local applications [19].

In the present work, the energetic and exergetic analysis is performed to the diesel engine based cogeneration system that considered by Salvador et al. [20] for combined power and heating applications and detailed formulations of energy and exergy efficiency are developed to the plant components and entire cogeneration plant. The objectives of this study are to calculate the exergy destruction within the plant and exergy loss to the environment and apply the performance assessment parameters to the components and entire cogeneration plant. The cogeneration system that was studied in this work is a very suitable choice to provide required work and heat for residential blocks, large markets, etc.

2. System description

Fig. 1 shows a schematic diagram of the system. The diesel engine intake air is first compressed to 3 bar absolute. Diesel engines are not limited by knock, and it is possible to feed these hot gases to the engine without intercooling, thereby improving the heating efficiency of the system. This improved heating efficiency is obtained at the expense of some loss of specific power due to the reduced density of the hot air, but this is considered a good trade off for cogeneration applications.

Compression ratio and equivalence ratio of the engine are (15:1) and 0.7, respectively. Also the fuel heating power into engine is 600 kW. The exhaust gases leaving the engine flow through the turbine of the turbocharger unit to produce necessary shaft work for the compressor. The cooling water loop goes from the engine to a heat exchanger being heated by the exhaust gases. Diesel engines can run with high temperature cooling water, and therefore no hot water from the engine needs to be wasted [20].

The following assumptions were made during this study:
- The diesel engine powered cogeneration system operates in a steady state condition.
- The ideal gas principles are applied to air and exhaust gases.

- For analysis of the diesel engine, the air standard dual cycle formulation is used.
- The combustion reaction in diesel engine is complete.
- The kinetic and potential energy changes are negligible.
- The dead properties are P_0=1 bar and T_0 =27 ˚C.
- Because the state of water in the exhaust is generally vapor in internal combustion engines, the lower heating value (LHV) of the fuel is used [8].
- All components were considered adiabatic, except the diesel engine.
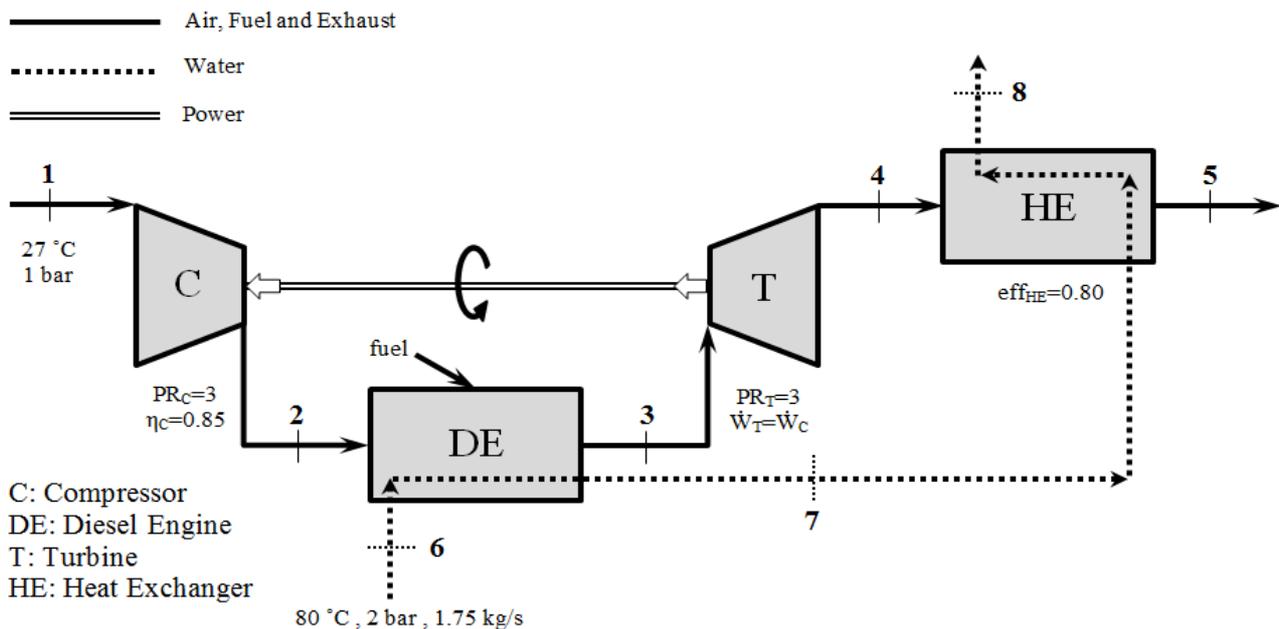
Fig. 1. A schematic diagram of the system

3. Energy and exergy relations

The energy balance equations for various parts of the CHP plant are as follows:

• Compressor

$$\frac{T_2}{T_1} = (\frac{P_2}{P_1})^{\frac{k-1}{k}} \tag{1}$$

• Diesel engine

Fig. 2 shows the state of the air inside the engine.

$$\frac{v_{1e}}{v_{2e}} = CR \tag{2}$$

$$\tag{3}$$

$$v_{3e} = v_{2e}$$
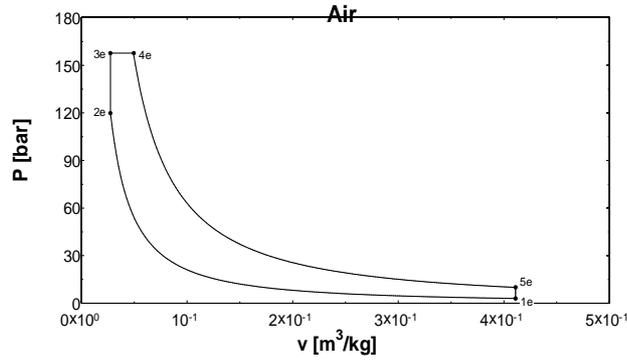
Fig. 2. P–v diagram of the diesel engine

$$x_f.\dot{Q}_{in} = (\dot{m}_a + \dot{m}_f).(h_{3e} - h_{2e}) \tag{4}$$

$$P_{4e} = P_{3e} \tag{5}$$

$$(1-x_f).\dot{Q}_{in} = (\dot{m}_a + \dot{m}_f).(h_{4e} - h_{3e}) \tag{6}$$

$$\frac{P_{5e}}{P_{4e}} = (\frac{T_{5e}}{T_{4e}})^{\frac{k}{k-1}} \tag{7}$$

• Turbine

$$\frac{T_4}{T_3} = (\frac{P_4}{P_3})^{\frac{k-1}{k}} \tag{8}$$

In above equations, *CR* is the compression ratio; x_f is the percentage of fuel that burns in constant volume and $\dot{Q}_{in}$ is the fuel heating power into the engine.

• Heat exchanger

$$(\dot{m}_a + \dot{m}_f).(h_4 - h_5) = \dot{m}_w.(h_8 - h_7) \tag{9}$$

Energy and exergy balances for a flow process in a system during a finite time interval may be written as:

Energy input – Energy output = Energy accumulation

Exergy input – Exergy output – Exergy consumption = Exergy accumulation

The above equations demonstrate that there is an important difference between energy and exergy, energy is conserved while exergy is consumed due to irreversibilities. Exergy indicates the quality of energy, and in any real process it is not conserved, but it is destroyed or lost [8].

Exergy can be divided into four distinct components. The two important ones are the physical exergy and chemical exergy. In this study, the two other components which are kinetic exergy and potential exergy are considered negligible as the elevation and speed have negligible changes. The physical exergy is associated with the work obtainable in bringing a stream of matter from its initial state to a state that is in thermal and mechanical equilibrium with the environment. The chemical exergy is associated with the work obtainable in bringing a stream of matter from the state that is in thermal and mechanical equilibrium with the environment to a state that is in the most stable configuration in equilibrium with the environment [21, 22].

Mass, energy and exergy balances for any steady state system can be written as [23]:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{10}$$

$$\dot{Q} + \sum \dot{m}_i h_i = \dot{W} + \sum \dot{m}_e h_e \tag{11}$$

$$\dot{E}_Q + \sum \dot{m}_i e_i = \dot{E}_W + \sum \dot{m}_e e_e + \dot{E}_D \tag{12}$$

Where subscripts *i* and *e* are the specific exergy of control volume inlet and outlet flow and $\dot{E}_D$ is the exergy destruction. Other terms in this equation are:

$$\dot{E}_Q = \sum (1 - \frac{T_0}{T_i})\dot{Q}_i \tag{13}$$

$$\dot{E}_W = \sum \dot{W} \tag{14}$$

$$\dot{E} = \dot{E}_{ph} + \dot{E}_{ch} \tag{15}$$

$$\dot{E} = \dot{m}e \tag{16}$$

$$e_{ph} = (h - h_0) - T_0(s - s_0) \tag{17}$$

The chemical exergy of the mixture is defined as follows [24, 25]:

$$e_{ch}{}^{mix} = \left[\sum_{i=1}^{n} X_i e_{ch_i} + RT_0 \sum_{i=1}^{n} X_i Ln(X_i) \right] \tag{18}$$

The chemical exergies of liquid fuels (LF) as C_aH_b on a unit mass basis can be determined from [26]:

$$\frac{e_{ch,LF}}{LHV_{LF}} = \gamma_{LF} \cong 1.04224 + 0.011925\frac{b}{a} - \frac{0.042}{a} \tag{19}$$

Where *γ* denotes the fuel exergy grade function.

The exergy destruction in steady flow operation of a component may be obtained from:

$$\dot{E}_D = T_0 \dot{S}_{gen} \qquad (20)$$

Where $\dot{S}_{gen}$ is the rate of entropy generation in the component.

Thermodynamic analysis of a power system usually includes the assessment of individual performances of system components.

The first law efficiency of system components can be calculated from following relations:

$$\eta_C = \frac{w_s}{w_a} \qquad (21)$$

$$\eta_T = \frac{w_a}{w_s} \qquad (22)$$

Where w_a and w_s are the actual and isentropic works, respectively.

$$\eta_{DE} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{m}_f LHV} \qquad (23)$$

The second law efficiency for system components can be given:

$$\eta_{C,II} = \frac{w_{rev}}{w_a} = \frac{h_e - h_i - T_0(s_e - s_i)}{h_e - h_i} \qquad (24)$$

$$\eta_{T,II} = \frac{w_a}{w_{rev}} = \frac{h_i - h_e}{h_i - h_e - T_0(s_i - s_e)} \qquad (25)$$

$$\eta_{HE,II} = \frac{(\dot{E}_e - \dot{E}_i)_{cold}}{(\dot{E}_i - \dot{E}_e)_{hot}} \qquad (26)$$

$$\eta_{DE,II} = \frac{\dot{W}_{net}}{\dot{E}_f} = \frac{\dot{W}_{net}}{\dot{m}_f e_f} \qquad (27)$$

Utilization efficiency for the entire diesel engine cogeneration system may be defined as:

$$\eta_{cogeneration} = \frac{\dot{W}_{net} + \dot{Q}_{process}}{\dot{Q}_{in}} = \frac{\dot{W}_{net} + \dot{m}_w(h_e - h_i)}{\dot{m}_f LHV} \qquad (28)$$

Where $\dot{Q}_{process}$ is the rate of process heat generated in the cogeneration plant.

Similarly the exergetic efficiency for the entire diesel engine cogeneration system may be expressed as:

$$\eta_{cogeneration,II} = \frac{\dot{W}_{net} + \dot{E}_{process}}{\dot{E}_{in}} \qquad (29)$$

A detailed exergy analysis of a power system should include calculating the exergy destruction in each component and relate this to the exergy of the fuel and to the total exergy destruction in the system [27]. The exergy destruction in steady flow operation of a component may be obtained using (20). The rate of exergy destruction in a component can be compared with the exergy rate of the fuel provided to the overall system as [28]:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_f} \qquad (30)$$

Also, the component exergy destruction rate can be compared with the total exergy destruction rate within the system as:

$$y_{D,k}^* = \frac{\dot{E}_{D,k}}{\dot{E}_{D,total}} \qquad (31)$$

Table 1 shows the thermodynamic data of the cogeneration plant according to the nomenclature shown in Fig. 1. This data are obtained from developed EES [29] thermodynamic model for the system.

		Table 1. Thermodynamic properties of fluids in the diesel engine cogeneration system							
State no.	Fluid	T (°C)	P (bar)	h (kJ.kg^{-1})	s (kJ.kg^{-1}K^{-1})	$\dot{m}$ (kg.s^{-1})	e_{ph} (kJ.kg^{-1})	e_{ch} (kJ.kg^{-1})	$\dot{E}$ (kW)
1	Air	27	1	300.6	5.706	0.2936	0	0	0
2	Air	156.5	3	431.3	5.753	0.2936	116.7	0	34.27
3	Exhaust	635.5	3	942.7	6.547	0.3076	389.7	51.15	135.6
4	Exhaust	523.1	1	817.9	6.716	0.3076	214.2	51.15	81.63
5	Exhaust	176.5	1	451.7	6.114	0.3076	28.54	51.15	24.51
6	Water	80	2	335	1.075	1.75	17.65	0	30.88
7	Water	106.1	2	444.9	1.375	1.75	37.43	0	65.5
8	Water	120.2	2	509.3	1.542	1.75	51.85	0	90.73

4. Results and discussion

In diesel engine CHP systems, the main product is electricity and the produced steam may be called a byproduct. The fuel utilization efficiency of the overall diesel engine based cogeneration plant was found to be 90.47%. This is very high compared to thermal efficiencies of power plants whose sole purpose is production of electricity. The work output and heating power of the cogeneration system were calculated to be 250.4 kW and 304.9 kW, respectively. These values were found to be 251 kW and 295 kW in [20]. This indicates that the results of our model are in a good agreement in comparison with Ref. [20].

In defining the exergy flow through the components of the system, *fuel* and *product* terms must be identified for each component. The fuel represents the resources needed to generate the product and it is not necessarily restricted to be an actual fuel such as natural gas, oil, or coal. The product represents the desired result produced by the system. Both the fuel and the product are expressed in terms of exergy [21]. Definitions of the exergies of fuels $\dot{E}_F$ and products $\dot{E}_P$ for the components of the diesel engine based cogeneration system are given in Table 2.

The rate of exergy destruction for the components of the system as compared with the total fuel exergy input and total exergy destruction of the system, and also the values of the exergies of fuels and products are given in Table 3.

Table 3 shows that 39.31% of the exergy of fuel entering the plant is converted to electrical power and the remaining 60.69% is lost. The exergetic efficiency of the plant is obtained 51.08%. Total exergy destruction in diesel engine is 250.6 kW. It is 37.52% of the total exergy input and 82.93 % of the total exergy destruction in the plant.

Total exergy destruction in the diesel engine is mostly due to the highly irreversible combustion process in the engine. Exergy loss in the cogeneration system is equal to the exergy of stream leaving the heat exchanger exhausted to the environment. With the assumption of no heat loss in the components, the exergy loss in the components is zero.

Table 2. Definitions of the exergies of fuels $\dot{E}_F$ and products $\dot{E}_P$ for the components of the system

Component	$\dot{E}_F$	$\dot{E}_P$
Compressor	$\dot{W}_C$	$\dot{E}_2 - \dot{E}_1$
Diesel engine	$\dot{E}_f + \dot{E}_2 + \dot{E}_6$	$\dot{E}_3 + \dot{E}_7 + \dot{W}_{DE}$
Turbine	$\dot{E}_3 - \dot{E}_4$	$\dot{W}_T$
Heat Exchanger	$\dot{E}_4 - \dot{E}_5$	$\dot{E}_8 - \dot{E}_7$

The exergetic efficiencies of the compressor and turbine of the turbocharger are 89.28% and 71.13%, respectively. These rather high values indicate that the performance of turbocharger unit is in the desirable level. The least efficient component of the system is diesel engine. As previously stated, this is due to highly irreversible combustion process in the engine. Second least efficient component in the plant is heat exchanger with the efficiency of 44.18%. Exergy destructions of such heat exchange units in the plant are mostly due to the heat transfer across a high average temperature difference between the two streams.

5. Conclusions

The detailed thermodynamic analysis of the diesel engine based combined heat and power (CHP) system was performed. Exergy destruction within the components and entire plant and exergy loss to the environment were calculated. Also, fuel utilization efficiency, rate of power, and rate of process heat of the plant were determined. The results showed that the diesel engine and heat exchanger had lower exergetic efficiency and higher exergy destruction compared with other components of the system. Thus, more attention should be paid to these components, from exergy point of view. The results of the present study can be used as a basis for exergoeconomic analysis of the system.

Table 3. Exergetic analysis results

Components	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_D$ (kW)	$\dot{E}_L$ (kW)	y^* (%)	y (%)	η_{II} (%)
Compressor	38.38	34.27	4.12	0	1.36	0.62	89.28
Diesel Engine	702.1	451.5	250.6	0	82.93	37.52	39.31
Turbine	53.97	38.38	15.58	0	5.16	2.33	71.13
Heat Exchanger	57.12	25.23	31.88	0	10.55	4.77	44.18
Overall System	667.8	341.2	302.2	24.51	100	45.24	51.08

Nomenclature

e	specific exergy (kJ.kg^{-1})
$\dot{E}$	exergy rate (kW)
h	specific enthalpy (kJ.kg^{-1})
k	specific heat ratio
$\dot{m}$	mass flow rate (kg.s^{-1})
P	pressure (bar)
$\dot{Q}$	heat rate (kW)
R	gas constant (kJ.kg^{-1}K^{-1})
s	specific entropy (kJ.kg^{-1}K^{-1})
T	temperature (K)
v	specific volume (m^3.kg^{-1})
$\dot{W}$	work (kW)
X	mole fraction
$y_{D,k}$	component exergy destruction over total exergy input
$y^*_{D,k}$	component exergy destruction over total exergy destruction

Subscripts

1,…,8	state points
1e,…,5e	state points of the air inside the engine
a	air
ch	chemical
D	destruction
e	outlet
f	fuel
i	inlet
k	kth component
L	loss
ph	physical
Q	heat
w	water
W	work

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