

Exergetic ecological index as a new exergetic indicator and an application for the heat engines

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ABSTRACT

Aim of this paper is to present a new exergetic index. This index is called exergetic ecological index and it is adopted from the ecological function that provides opportunity to compare power output (desired output) and exergy destruction (lost power). The bigger ecological function means the more efficient and environmental friendly energy system. However, this criterion does not give any information about relation with the exergy source and exergetic ecological index provides this comparison. Finally, exergetic ecological function includes product exergy, exergy destruction and exergy source in a one equation and enables to evaluate any energy system considering with these three parameter.

1. Introduction

One of the most important concerns in the world is the environmental issues. Especially, global warming is focused on by the decision makers. The most important reason of the global warming is the emissions released to the atmosphere and ratio of the energy generating systems on the emission is considerable. Because of this, scientists and engineers attempt to design new technologies and more efficient energy generating systems.

Designing environmental friendly systems, one should analysis and optimize the cycle. Different methods are utilized to design and optimization processes. One of them is the exergy analysis. Exergy analysis enables someone to determine inefficiencies and their amount in a system. After determining them, improvement studies and procedures are applied. In this way, sustainability of a system can be enhanced. Rosen et al. pointed out interaction between exergy efficiency and the sustainability [1]. They expressed that increasing at the exergy efficiency is resulted in increasing at the sustainability. Connelly and Koshland, proposed a new index to explain depletion of energy source which has really close interaction with sustainability [2]. Exergy analysis can be even applied to different system including biology [3]. Another, method is finite time thermodynamics (FTT). Using FTT, actual heat engines can be modeled and optimization process can be performed more realistic. Some examples of the FTT can be found in refs. [4–22]. Ecological function proposed by the Angulo-Brown [23] is an another way to design more efficient and environmental friendly

system and it is modified by Yan [24]. In the literature, it can be found that application of the ecological function [25–43].

In this study, a new criteria called as exergetic ecological index is presented. This index is adopted from the ecological function. Importance of the ecological function enables someone to compare power output and exergy destruction. Power output is desired output while exergy destruction is wasted energy or lost power and it shows the balance between them. Ecological function should be as big as possible to prevent to waste at the energy source, thus, reducing at the emission released. However, ecological function does not show the interaction between the power output and exergy destruction with exergy source. On the other hand, exergetic ecological function shows that interaction with the exergy source and ecological function to determine how sustainable energy source is utilized. In addition, this index includes the product exergy, exergy destruction and exergy source and enables to consider these three parameters together. In second section, exergetic ecological index is explained in detail. In third section, an irreversible heat engine is defined and exergetic ecological index is utilized to it. In section four, results are presented and discussed.

2. Definition of exergetic ecological index

Engineers and scientists aim to produce maximum product by using minimum source. For an energy generating systems, this product is the power output. To evaluate an energy generation system, laws of thermodynamics are used. The most used criteria is energy efficiency

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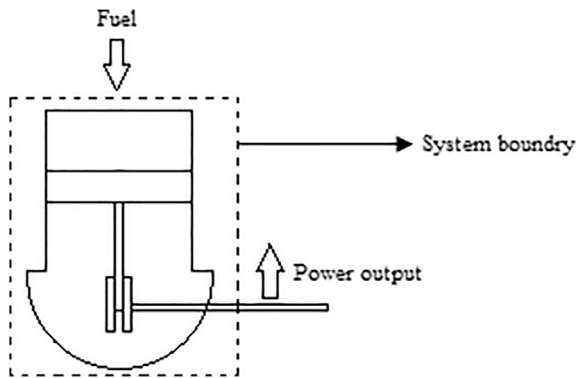


Fig. 1. Schematic of an internal combustion engine.

described by the first law of the thermodynamics. According to this law, difference of energy input to the system and energy output from the system is equal to stored energy in the system. So, energy is conserved and not destructed. In this definition, input energy is generally fuel energy and output is the power. In other words, fuel energy is converted to power output, however, not all fuel energy can be converted to power output and some portion of it is converted to energy that cannot be utilized in the system (this is called as lost energy). Let's assume an internal combustion engine (ICE), it is depicted in Fig. 1. In this system, fuel energy is turned into power output. This kind of system, effectiveness of the ICE is evaluated by using energy efficiency. Energy efficiency is described as ratio of power output to the fuel energy which is shown in Eq. (1). It is measure of the how succeeded energy source (in this case, it is fuel energy) is converted to product (in this case, power output). For instance; if energy efficiency is 0.30, this means only 30% of the energy source is turned into product and 70% of the energy source is lost. This is important not only energy saving and energy cost but also environmental protection. Because, more effective (a system has higher energy efficiency) systems consume less fuel to obtain same amount power, that's why, emission rate is decreased and environmental impact of it too.

$$\eta = \frac{\text{Product (Power Output)}}{\text{Source (Fuel Energy)}} \quad (1)$$

However, it is impossible to design a system has 100% energy efficiency and some portion of the energy has to be rejected from the system, because of the second law of the thermodynamics. Although, first law of the thermodynamics is required to establish energy balance, it gives information about only quantity of the energy not quality of the energy. Second law of the thermodynamics is a very useful tool to assess energy systems via exergy analysis. Exergy is measure of the maximum energy obtained from an energy source, in other words, exergy represents quality of the energy. In contrast to energy, exergy is not conserved and some portion of exergy is always destructed. This destruction is resulted from the irreversibilities or entropy generation. Power output is product exergy ($\dot{E}x_p$) which means desired output, exergy of the fuel is called as fuel exergy ($\dot{E}x_f$) which is defined as expense in exergetic resources for the generation of the product exergy and exergy destruction ($\dot{E}xD$) is the lost power of wasted power resulted from the irreversibilities. Relations between fuel exergy rate, product exergy rate and exergy destruction rate is written in Eq. (2).

$$\dot{E}x_f - \dot{E}x_p = \dot{E}xD \quad (2)$$

Using exergy analysis, irreversibilities (main reason of the inefficiencies) can be defined and their amounts can be calculated. At the next step, these irreversibilities are tried to improve. Main exergetic evaluation criterion is the exergy efficiency, which is measure of how a system is close to reversible one. Reversible system provides the maximum power output and it does not include any irreversibility. For the explain to exergetic efficiency, let's consider ICE at the Fig. 1. In this

system, product exergy is the power output, and exergy of the fuel is the exergy source (fuel exergy). One can yields exergy efficiency as:

$$\varphi = \frac{\text{Product Exergy (Power Output, } \dot{E}x_p)}{\text{Exergy Source (Exergy of fuel, } \dot{E}x_f)} \quad (3)$$

Using exergy efficiency, it can be determined how much fuel exergy can be converted to product exergy (in this case, power output). Assuming exergy efficiency is 30% and fuel exergy rate is 100 kW, one can found that product exergy (power output) is 30 kW and using Eq. (2) exergy destruction rate can be calculated as 70 kW. So, lost power is about 2.33 of the useful power and this means that 70% of the exergy sources is wasted. As can be predicted, exergy destruction rate is directly related with the environmental issues. Because, the bigger exergy destruction means the bigger wasted exergy (or energy) and the bigger emission rate. Depletion ratio is proposed [2] as measure of the depleted exergy sources. It is described rate of the exergy destruction to fuel exergy and it is shown in Eq. (4):

$$DP = \frac{\text{Exergy Destruction (Lost Power, } \dot{E}x_p)}{\text{Exergy Source (Fuel Energy, } \dot{E}x_f)} \quad (4)$$

Increasing DP causes to waste of sources and increasing environmental impact. According to expressions above, relations energy, exergy and environmental impacts are shown. In the literature, a criterion to determine more efficient and more environmental friendly system was proposed called as ecological function [22,23]. Ecological function enable someone to compare power output and exergy destruction. It is described as follows:

$$\dot{E} = P - T_0 \dot{S}_{gen} \quad (5)$$

First term at the right side is the power output (product exergy, useful power) and second term is the exergy destruction rate (lost power). It shows that difference of the useful power and wasted power and at the positive values of the ecological function, power output is bigger than the lost power and at negative values vice versa. For the example, exergy efficiency of the ICE is 30%, power output is 30 kW and exergy destruction is 70 kW and ecological function is -40 kW. Although it shows the relation between product exergy and lost power and environmental impact of the system, it does not give any information relation with the exergy source. An equation should be derived from ecological function involving the exergy source. By dividing ecological function to fuel exergy, a new criterion can be obtained as follows:

$$\frac{\dot{E}}{\dot{E}x_f} = \frac{P}{\dot{E}x_f} - \frac{\dot{E}xD}{\dot{E}x_f} \quad (6)$$

and Eq. (6) can be expressed as follows:

$$\xi = \varphi - DP \quad (7)$$

where, ξ is called as exergetic ecological index and φ represents ratio of the product exergy to fuel exergy, which means useful part of the fuel exergy, and DP represents ratio of de lost power to the fuel exergy, which means wasted part of the fuel exergy. This index provides not only comparison of the useful and wasted power but also comparison with the exergy source. In addition, exergetic ecological index includes all exergetic parameters, and enable us to evaluate a considered system using all exergetic parameters. In the optimization studies, one should avoid from negative values and small values.

3. Application to a heat engine

A heat engine is defined in this section. It is assumed heat source and heat sink temperatures are constant and they are T_H , T_L respectively. Heat engine operates in steady state conditions and heat losses are neglected. T_h and T_l are the temperatures of hot working fluid and cold working fluid respectively. Finally, k_H (kW/K) and k_L (kW/K) are

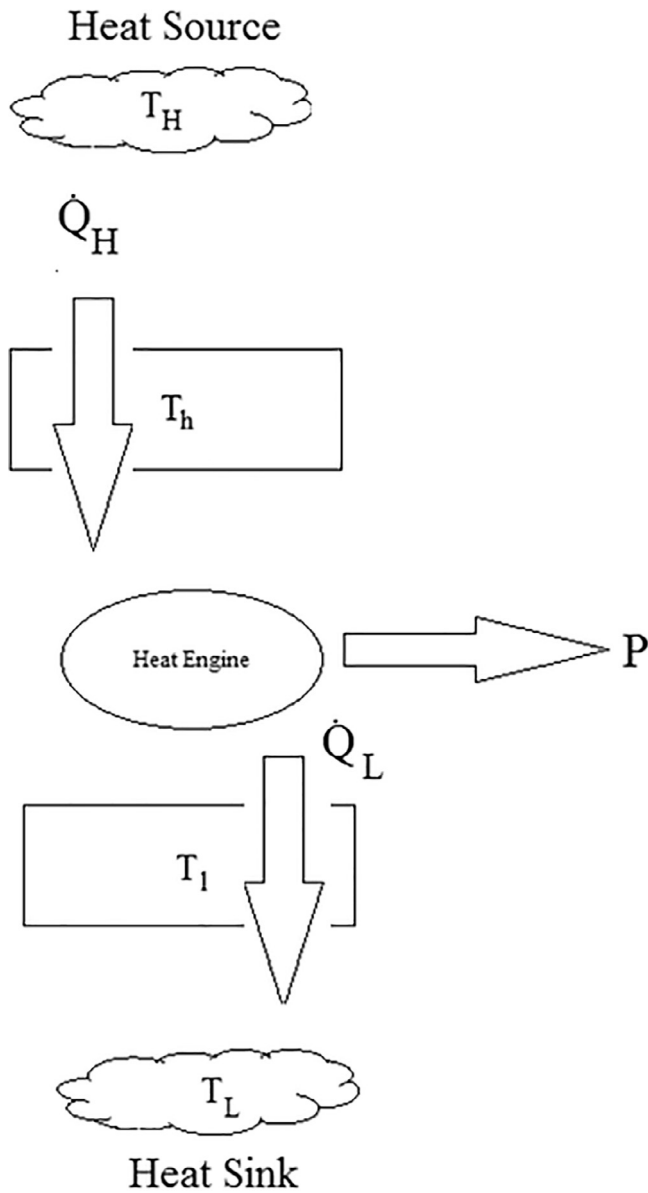


Fig. 2. Irreversible heat engine.

heat conductance of the hot and cold side and I is the internal irreversibility factor. Considered heat engine is schematized in Fig. 2. Methodology in Refs. [37,38] are adopted in the calculations. Heat input rate is (kW):

$$\dot{Q}_H = k_H(T_H - T_h) \quad (8)$$

heat output rate is (kW):

$$\dot{Q}_L = k_L(T_l - T_L) \quad (9)$$

From the first law of the thermodynamics, power output is written as (kW):

$$P = \dot{Q}_H - \dot{Q}_L \quad (10)$$

From the second law of the thermodynamics:

$$I \frac{\dot{Q}_H}{T_h} = \frac{\dot{Q}_L}{T_l} \quad (11)$$

defining some parameters as follows:

$$y = \frac{k_L}{k_H}, \quad z = k_H + k_L, \quad x = \frac{T_l}{T_h} \quad (12)$$

heat input rate is:

$$\dot{Q}_H = \frac{z}{1+y} \frac{y(T_H x - T_L)}{x(y+1)} \quad (13)$$

heat output rate:

$$\dot{Q}_L = I \dot{Q}_H x \quad (14)$$

Fuel exergy rate (kW):

$$\dot{E}x_F = \dot{Q}_H \left(1 - \frac{T_o}{T_H}\right) \quad (15)$$

Product exergy rate (kW):

$$\dot{E}x_P = P \quad (16)$$

Exergy destruction rate (kW):

$$\dot{E}x_D = \dot{E}x_F - \dot{E}x_P \quad (17)$$

Energy efficiency is:

$$\eta = \frac{P}{\dot{Q}_H} \quad (18)$$

Exergy efficiency is:

$$\varphi = \frac{P}{\dot{E}x_F} \quad (19)$$

Depletion ratio:

$$DP = \frac{\dot{E}x_D}{\dot{E}x_F} \quad (20)$$

exergetic ecological index is described as:

$$\xi = \varphi - DP \quad (21)$$

For better understanding, dimensionless power output, exergy destruction, fuel exergy and ecological function are obtained:

$$p = \frac{P}{P_{\max}}, \quad exd = \frac{\dot{E}x_D}{\dot{E}x_{D_{\max}}}, \quad ex_f = \frac{\dot{E}x_F}{\dot{E}x_{F_{\max}}}, \quad e = \frac{\dot{E}}{\dot{E}_{\max}} \quad (22)$$

4. Results and discussions

Results of application of the exergetic ecological index are presented and discussed. Dimensionless power output, exergy destruction rate, fuel exergy and ecological function have obtained. In Figs. 3 and 4, results can be seen for the dimensionless power output, exergy destruction rate, fuel exergy rate and ecological function as well as, energy efficiency, exergy efficiency, depletion ratio and exergetic ecological index. In addition, η - e - p and φ - DP - ξ - p curves are depicted. Operation range of the heat engine is determined as $0.26 \leq x \leq 0.95$. In calculations, $T_H = 1200$ K, $T_L = 310$ K, $T_o = 300$ K, $I = 1.05$, $y = 1$, $z = 1$ kW/K are applied.

Variation of the dimensionless power output (p), exergy destruction rate (exd), fuel exergy rate (ex_f) and ecological function (e) could be seen in Fig. 3. As it can be seen that p and e have maximum (optimum) points. Dimensionless power output reaches its maximum at the $x = 0.5$ and e reaches its maximum at the $x = 0.39$. Optimum points of the power output and ecological function are not at the same point. This means that, at the maximum power output, difference of the power output and the exergy destruction rate is not maximum and it can be found that there is another point where ratio of the power point to the exergy destruction is bigger. This is important, because, according to Fig. 3, there are a lot of point where ecological function is negative. So, at these points, exergy destruction values are bigger than power output values. This means, in these points, lost power is bigger than the useful power and most of the fuel exergy rate is depleted, that's why, environmental impact of the considered thermal system is risen up. Dimensionless exergy destruction rate (exd) increases with x and this

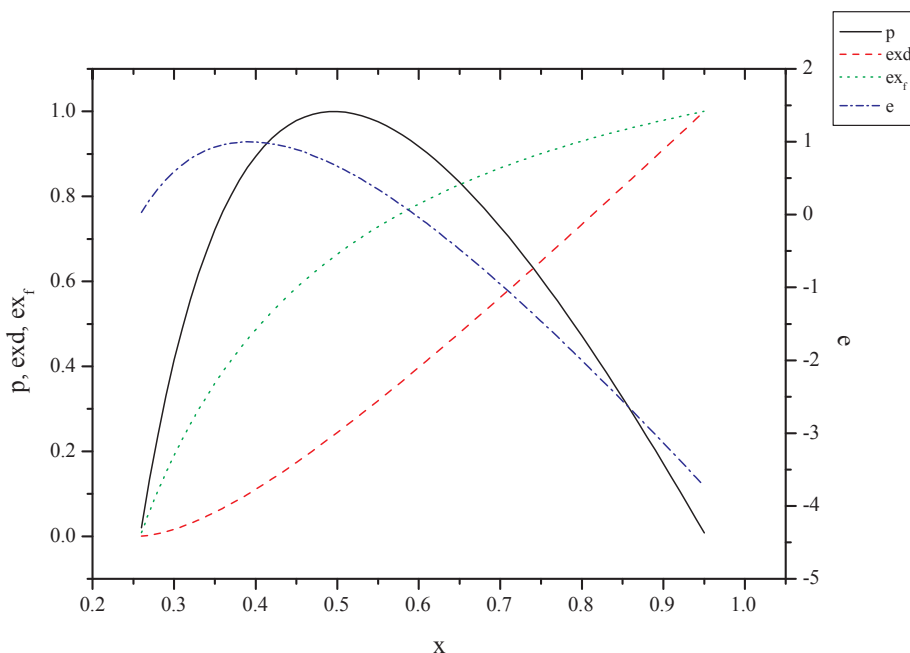


Fig. 3. Variation of the dimensionless power, exergy destruction, fuel exergy and ecological function.

increase is nearly linearly. Maximum value of the exd is obtained at $x = 0.95$, as it is seen in Fig. 3 and same situation is correct for the dimensionless fuel exergy (ex_f). Exergy destruction rate is called lost power which means useless power output or depleted source. This lost power cannot be used anymore and fuel exergy is wasted. Emission or environmental impact increases because of this lost power and exergy destruction rate should be minimized. Exergy efficiency (φ), energy efficiency (η), depletion ratio (DP) and exergetic ecological index (ξ) are shown in Fig. 4. They are decreasing linearly with x except for DP . Decreasing rates of the φ , η , DP are nearly 100% and φ , η , and ξ get their maximum values at $x = 0.26$, while DP gets its maximum at $x = 0.95$. One can see that φ , η , ξ are inversely proportional with DP . This is expected result, because, DP represents the depletion of the fuel

exergy (exergy source). So, DP is the rate of exergy destruction (lost work or destructed exergy) to fuel exergy and increasing DP leads decreasing at the exergy efficiency, energy efficiency and exergetic ecological index. Exergy efficiency is the measure of how close a thermal system is to reversible one and if fuel exergy is constant, increasing exergy destruction, in other words increasing at the DP , leads decreasing at the exergy efficiency. In addition, exergy destruction or lost work means inefficiencies in the thermal system. That's why, increasing at the DP causes to decrease at the energy efficiency too. Because, the bigger exergy destruction rate means the smaller useful power output, if fuel exergy is constant. For the exergetic ecological index, same result are correct. Since, ξ is the difference of the exergy efficiency and the depletion ratio, in other words difference of useful power and the lost

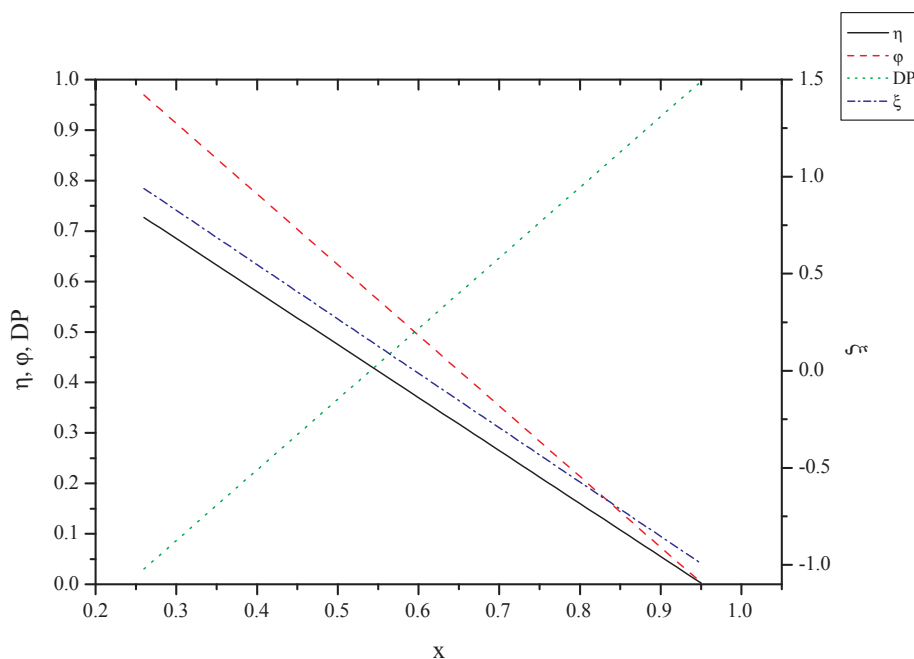


Fig. 4. Variation of the energy efficiency, exergy efficiency, depletion ratio and exergetic ecological index.

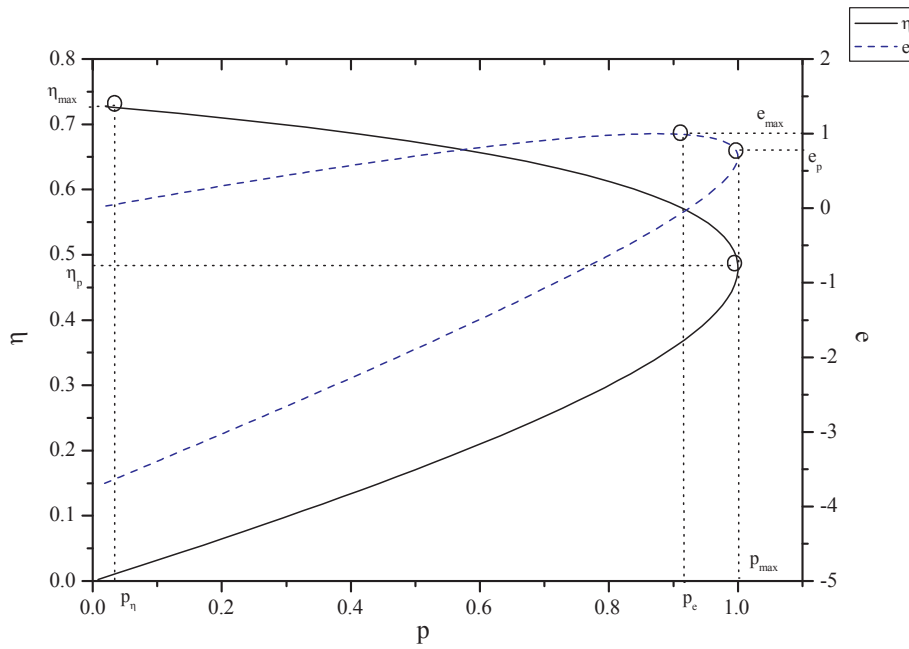


Fig. 5. η - e - p curve.

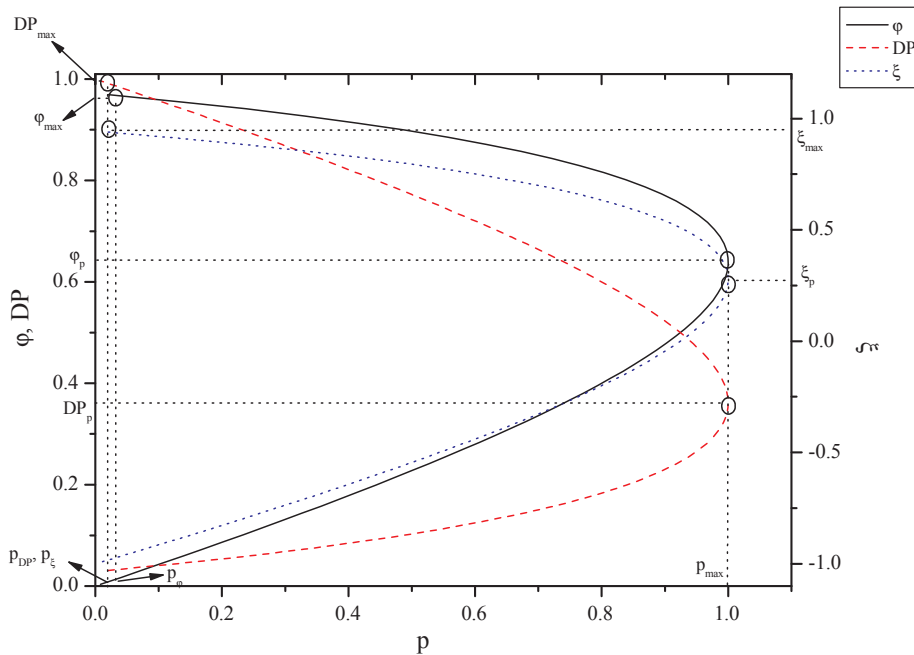


Fig. 6. ϕ - DP - ξ - p curve.

power, increasing at the exergy destruction causes decreasing at ξ . In addition, if rate of increasing at the exergy destruction rate is bigger than the rate of increasing at the power output, then, exergetic ecological index gets negative values and it should be avoided from these negative points. Another important point is that proportion part (or ecological function) can be compared with fuel exergy. However, ecological function does not give any information about relation with fuel exergy in contrast to exergetic ecological index. Range of the exergetic ecological index is $-1 < x < 1$. For example, according to results, exergetic ecological index is 0.939 at the $x = 0.26$, this means more than 90% of the fuel exergy is converted to power output. Similarly, at the $x = 0.95$, it is equal to -0.993 which means exergy destruction rate is bigger than the power output and more than 99% of the fuel exergy is destroyed. In contrast to ecological function, exergetic ecological index

has no optimum point, this is resulted from the effect of the fuel exergy. So, it can be said that exergetic ecological index should be considered for optimization process, since, this index provides relation between fuel exergy, product exergy and exergy destruction at the same time. Environmental effects are smaller, when ϕ , η and ξ get bigger values and vice versa for the DP . In Fig. 5, p - η - e curve is depicted, where e_{max} is the maximum ecological function, p_{max} is the maximum power output, η_{max} is the maximum energy efficiency, e_p is the ecological function at the maximum power output, p_η is the power output at the maximum energy efficiency and η_p is the energy efficiency at the maximum power output. Investigating the results, one can see that e_p is equal to 66% of its maximum, p_η is equal to 13% of its maximum and η_p is the 66% of the maximum efficiency. In addition, p_e is the 87% of the maximum power output, η_e is equal to 86% of the maximum efficiency, e_η is the

20% of the its maximum. Another evaluation criteria is the exergy destruction rate, According to results, exergy destruction rate is equal to 25% of its maximum at the maximum power output, while it is equal to 0.3% of its maximum at the maximum efficiency and 10% at the maximum ecological function. Conventionally, x should be chosen between $x_{\eta} \leq x \leq x_p$, where x_{η} is the x at the maximum efficiency and x_p is x at the maximum power output. When investigating the results, operating heat engine at the ecological function cause nearly 13% decreasing at the maximum power and 18% decreasing at the maximum efficiency and if these results are compare other maximum points, there is 34% decreasing at the efficiency at the maximum power output, and 87% decreasing at the power output at the maximum efficiency. When interpreting these results, a heat engine can be operated at the ecological function more effectively instead of maximum efficiency or maximum power output. In Fig. 6, p - φ - DP - ξ curve is shown, where φ_{max} is the maximum exergy efficiency, DP_{max} is the maximum depletion ratio, ξ_{max} is the maximum exergetic ecological index, φ_p is the exergy efficiency at the maximum power output, DP_p is the depletion ratio at the maximum power output, ξ_p is the maximum exergetic ecological index at the maximum power output, p_{φ} is the power output at the maximum exergy efficiency, p_{DP} is the power output at the maximum depletion ratio, p_{ξ} is the power output at the maximum exergetic ecological index. According to results, φ_p is 66% of its maximum, DP_p is 36% of the its maximum and ξ_p is the 30% of its maximum, similarly p_{φ} , p_{DP} and p_{ξ} are equal to 13%, 0.8% and 13% of the maximum power output respectively. Exergydestruction rate is equal to 0.3% of its maximum at the maximum exergy efficiency, 100% at the maximum depletion ratio and 0.3% at the maximum exergetic ecological index.

Interpreting these results, optimization range of the considered heat engine should be chosen as $x_{\xi} \leq x \leq x_e$, where x_{ξ} is the x at the maximum exergetic ecological index and x_e is x at the maximum ecological function.

In this paragraph, similarities and differences ecological function and exergetic ecological index are shown. First difference, exergetic ecological index shows how much fuel exergy converts to product exergy and how much fuel exergy is destroyed. Ecological function doesn't provide any information like that, since ecological function only shows the difference between product exergy and exergy destruction as well as which one of them is bigger. For example, ecological function density is 0.592 and exergetic ecological function is 0.827 for the $x = 0.3$. This provides information about the exergy product is bigger than exergy destruction for the ecological function, however, if exergetic ecological function is evaluated, one can see that 0.827 of the fuel exergy is converted to product exergy and rest of it is converted to exergy destruction which is 0.173. One can see that most of the fuel exergy is turned to product exergy and product exergy is bigger than exergy destruction. Another difference is ecological function gives an optimum between product exergy and exergy destruction contrast to exergetic ecological function. Similarity between these two criteria is that negative values show that product exergy is bigger than the exergy destruction and vice versa is true for the positive values.

5. Conclusions

In this study, a new index called as exergetic ecological index is proposed. Its physical meaning is explained in detail and relation between sustainability is shown. A heat engine is considered for application of exergetic ecological index and results are obtained, discussed and compared with energy efficiency, exergy efficiency, depletion ratio, power output, exergy destruction and fuel exergy. This index is proposed to use in optimization process of the heat engines, because it includes three exergy parameter which are fuel exergy, product exergy and exergy destruction. It provides anyone to compare power output, exergy destruction and fuel exergy. Finally, it is determined operation range of the heat engine should be chosen as $x_{\xi} \leq x \leq x_e$. It is recommended that exergetic ecological function should be applied and

evaluated for different energy systems.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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