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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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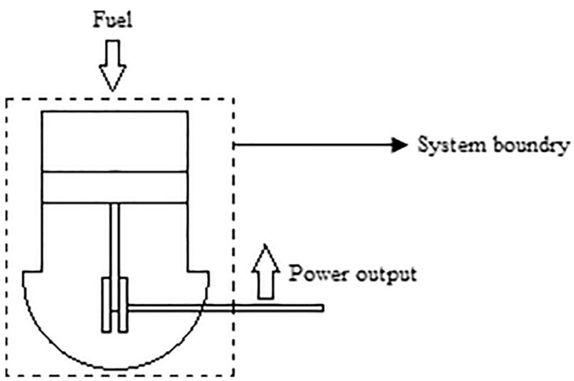

Fig. 1. Schematic of an internal combustion engine.

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 in to 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.

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

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 (Ex_P) which means desired output, exergy of the fuel is called as fuel exergy (Ex_F) which is defined as expense in exergetic resources for the generation of the product exergy and exergy destruction (ExD) 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).

$$\dot{E}x_F - \dot{E}x_P = \dot{E}xD \tag{2}$$

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:

$$\varphi = \frac{Product\ Exergy\,(Power\ Output,\ \dot{E}x_P)}{Exergy\ Source\,(Exergy\ of\ fuel,\ \dot{E}x_F)} \tag{3}$$

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):

$$DP = \frac{Exergy\ Destruction\,(Lost\ Power,\ \dot{E}x_P)}{Exergy\ Source\,(Fuel\ Energy,\ \dot{E}x_F)} \tag{4}$$

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:

$$\dot{E} = P - T_o\dot{S}_{gen} \tag{5}$$

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:

$$\frac{\dot{E}}{\dot{E}x_F} = \frac{P}{\dot{E}x_F} - \frac{\dot{E}xD}{\dot{E}x_F} \tag{6}$$

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

$$\xi = \varphi - DP \tag{7}$$

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

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