Third approach in work loss phenomenon

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Abstract. One of the most widespread irreversible processes in technique is the heat transfer from the higher to the lower body temperature. The main reason for this is due to the necessity of significant temperature difference in order to achieve a satisfactory process speed. Maximum work for the same heat amount (the same temperature level) will achieve reversible (ideal) system. The heat exergy represents maximum part of the heat that can be converted into work. In the system in which real processes take place, there is an increase of entropy and loss of work (exergy). This is the main reason for the low efficiency of the system for the transformation of heat energy into work. This phenomenon can be proven by different approaches. The first law of thermodynamics is mainly used for the analysis of energy utilization. The second law of thermodynamics and exergy analysis as its consequence, is more relevant for qualitative aspects of used or consumed energy. This paper presents third approach how exergy losses can be defined and its impacts on energy efficiency of the system.

1. Introduction

Exergy analysis is known as a useful tool that can be utilized to evaluate the performance of any engineering system [1]. Energetic and exergetic assessment of a process deals with the first and second law of thermodynamics, respectively. Eventhough, first law of thermodynamics is mainly used, it doesn't posess ability to analyze qualitative aspects of used or consumed energy. Exergy, as a consequence of second law of thermodynamics, can be used for such a analyzes.

Exergy is the maximum theoretical useful word (shaft work or electrical work) obtainable from a system as this is brought into thermodynamic equilibrium with the reference environment while the system interacts only with this environment. Alternatively the exergy can be defined as the minimum theoretical work required to form a quantity of matter from substances present in the reference environment and to bring this matter to a specific thermodynamic state. The exergy is a measure of the departure of the state of a system from the state of the reference environment [2].

Exergy analysis [3-10] is a methodology that uses the conservation of energy principle (embodied in the first law of thermodynamics) together with non-conservation of entropy principle (embodied in the second law) for the analysis, design and improvement of energy and other systems. Since exergy is always a measure of the approach to ideal, exergy analysis enables design more efficient energy systems by reducing inefficiencies.

Energy efficiencies do not define how nearly performance aproaches ideality but exergy efficiency does. There are now many papers introducing principles and methods of exergy analysis [1-11]. Exergy destruction and irreversibilities which is similar in a sense of loss during the process gives more realistic system losses than energy losses [11]. Exergy analysis can, therefore, indicate the possibilities for thermodynamic improvement. The term exergy was first mentioned at the conference in Lindau in 1953 by Z. Rant. The term exergy originates from the "ex" before "ergy", and the meaning is "from" and "work", and characterizes the work that can be obtained from the system [12].

Heat (as a form of energy) can be divided into into one part that can produce work (its Exergy), and one part that can not be used to produce work, which is commonly referred to as Anergy [13]. For heat Q at temperature T, the following decomposition can be made with reference to the ambient temperature T_o:

$$Energy = Exergy + Anergy$$

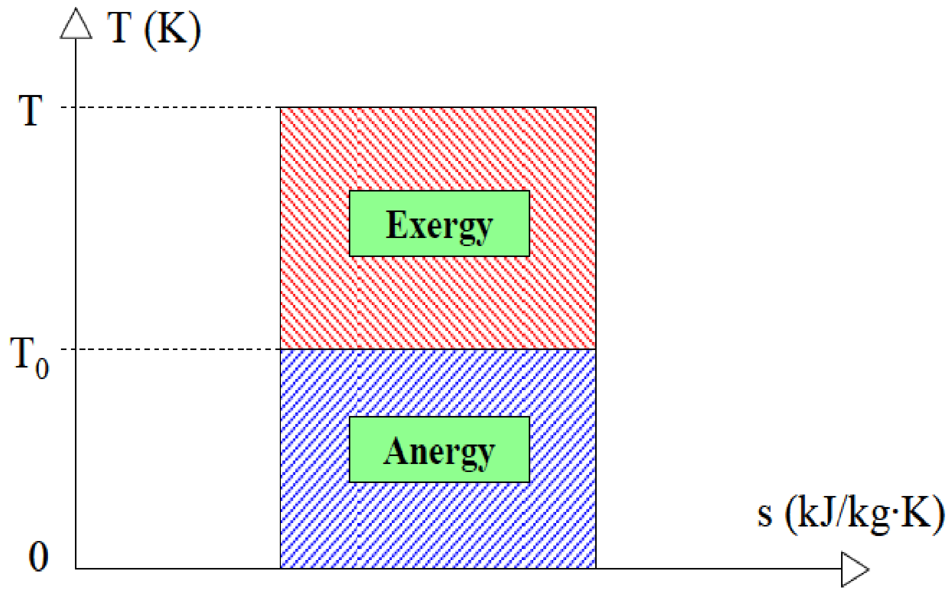

Figure 1. Decomposition of Energy (Heat) into Exergy and Anergy [13]

First law of thermodynamic says that amount of energy that enters the system is the same one that comes out of the system in accordance with the law of conservation of energy. Second law says that the amount of entropy that comes out of the system is greater than the one that enters the system in accordance with the law of increasing entropy.

One of the most widespread irreversible processes in technique is the heat transfer from the higher to the lower body temperature. The main reason for this is due to the necessity of significant temperature difference in order to achieve a satisfactory process speed. All technical systems in which heat is converted into work (motors, thermal power plants, etc.) still are considerably behind ideal ones. All these processes are irreversible. The heat exergy represents maximum part of the heat that can be converted into work. In the system in which real processes take place, there is an increase of entropy and loss of work (exergy). This is the main reason for the low efficiency of the system for the transformation of heat energy into work. The maximum work for the same amount of heat (the same temperature level) will achieve the ideal (reversible) system.

The classification of exergy can be done in the way similar to classification of energy, with some exceptions. In this paper, emphasis is on thermodynamic and heat converted into work relations so thermo-mechanical exergy can be classified as it's shown on Figure 2.

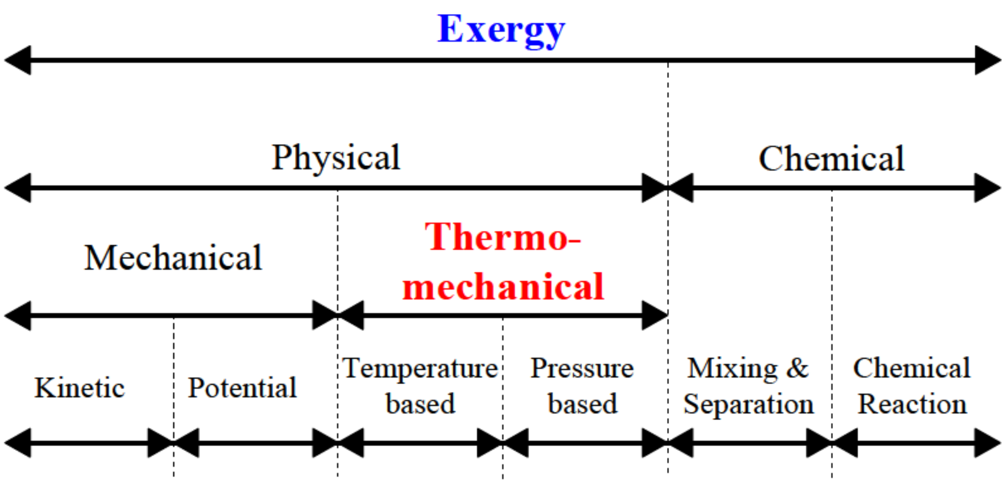

Figure 2. Classification of exergy for pVT systems [13]

The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process. Exergy is also a measure of the potential to cause change, as a consequence of not being in equilibrium relative to the reference environment [14]. It can be said that exergy is a concept that connects the universal concept of entropy to the conditions on Earth through temperature. The loss of exergy (work) is determined as a product of ambient temperature and entropy increment within the system's control boundary: This term in the literature is called the "Gouy - Stodola rule" according to French physicist Gouy and the Slovak engineer Stodola.

This is analitical approach for exergy analyze. Taking into consideration ambient temperature as one of the criteria for thermodynamic analyzes of systems which are operating in the temperature range "far from the ambient temperature" led some researchers to doubts about the validity of the exergetic method as a tool for thermodynamic analysis. A more extensive critique of exergetic analysis is presented in [15] and [16].

2. Analitical approach

Entropy of an isolated system grows if even the smallest part of its process is irreversible. This is always the case in the conditions on Earth, where the changes of the state are irreversible, and the consequence of this is the so-called “degradation” of energy. What really means energy “degradation”? This is to say that the heat as a form of energy has a lower quality than other forms (mechanical, electric, etc). This is in cases where heat participates in the process and there is irreversibility and losses (conversion various forms of energy into heat at the ambient temperature) [17]. In fact, there is no purely mechanical process because always with every mechanical movement friction occurs. Duo to that one part of the mechanical energy is transformed into a heat and such a mechanical process (with friction, with the appearance of heat) is not reversible. So, a purely mechanical process would be without friction, and in that case it would be completely reversible. Friction is a cause of irreversibility, a cause of energy “degradation”, and hence itself makes a non-return process. A process is reversible if, after the process is completed, all system and all its elements and surroundings can be restored to their respective initial states. When there is a friction in process, mechanical energy (spent work) turns into heat:

$$W = Q. \tag{1}$$

Based on well-known equation for the Carnot cycle efficiency of an engine operating between two fixed temperatures:

$$\eta_C = \frac{Q - Q_O}{Q} = \frac{W_k}{Q} = \frac{T - T_O}{T}, \quad (2)$$

It is possible get maximum work in reversible process:

$$W_{max} = W_k = \eta_C Q = Q\frac{T - T_O}{T}, \quad (3)$$

where W_k is obtained work which is also maximum work of the system because it is obtained with Carnot cycle; T_o is ambient temeprature and T temeprature of the system. Difference between spent work duo to friction (W) and maximum work (W_{max}) which could be obtained from heat (Q) with Carnot cycle is:

$$W - W_{max} = Q - Q\frac{T - T_O}{T} = Q\left(1 - \frac{T - T_O}{T}\right) \quad (4)$$

$$\Delta W = W - W_{max} = Q\frac{T_O}{T} = \frac{Q}{T}T_O = \Delta S T_O \quad (5)$$

From this it can be seen that the difference in work (i.e. loss in work due to irreversibility) is product of the ambient temperature and the increase in entropy (due to friction). So, it can be said that the work loss due to irreversibility is proportional to the entropy increase. Expression 5 is also known as a Gouy-Stodola theorem for the lost work. Hence, lost work is proportional to the entropy generation rate.

3. Graphical approach

In order to prove the necessity of ambient temperature in the criteria for thermodynamic evaluation of systems which are operating in the temperature level "far from" the ambient temperature or in a technological process when they do not have a direct connection with the environment, in [18], [19] is developed graphical interpretation of exergy losses in T-s diagram. Figure 3 represents heat exchange between flows of the same substance (same mass flows) which change a phase. In second stream is process of condensation and in first is evaporation. The temperature difference is due to different pressures in flows.

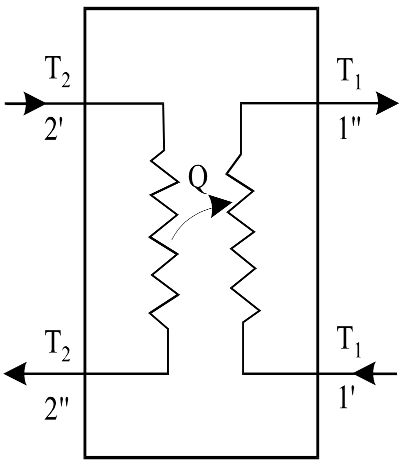

Figure 3. Exchange of heat between flows of the same substance

If in the T-s diagram (Figure 4) there is a change state of both flows, where is $T_2 > T_1 > T_0$, it follows that the surface 2'2"a'b" represents the heat taken from 1kg of flow two, and the surface 1'1"c'a' presents heat brought to 1kg of flow one. Due to the equality of heat, the equality of surfaces is also followed (the sum of 2'2"a'b'= Q_2 = Q_1 = surface 1'1"c'a"). The equality of these surfaces follows from the applied structures of the rectangle a'c'e2". On the same heat exergy diagram, the surfaces are represented by flow 2 (E_2 = surface 2'2"ab) and flow 1 (E_1 = surface1'1"ca). The loss of work during heat transfer from a higher to a lower temperature level is equal to the difference between the exergy, that is, the surface 2'2"ab minus the surface1'1"ca. Graphical construction applied in Figure 4 also shows that the difference in these surfaces is equal to the surface of bccb'. From the same image, it is seen that this surface is equal to the product of the ambient temperature and the increase in entropy in the system, which is the Gouy-Stodola rule.

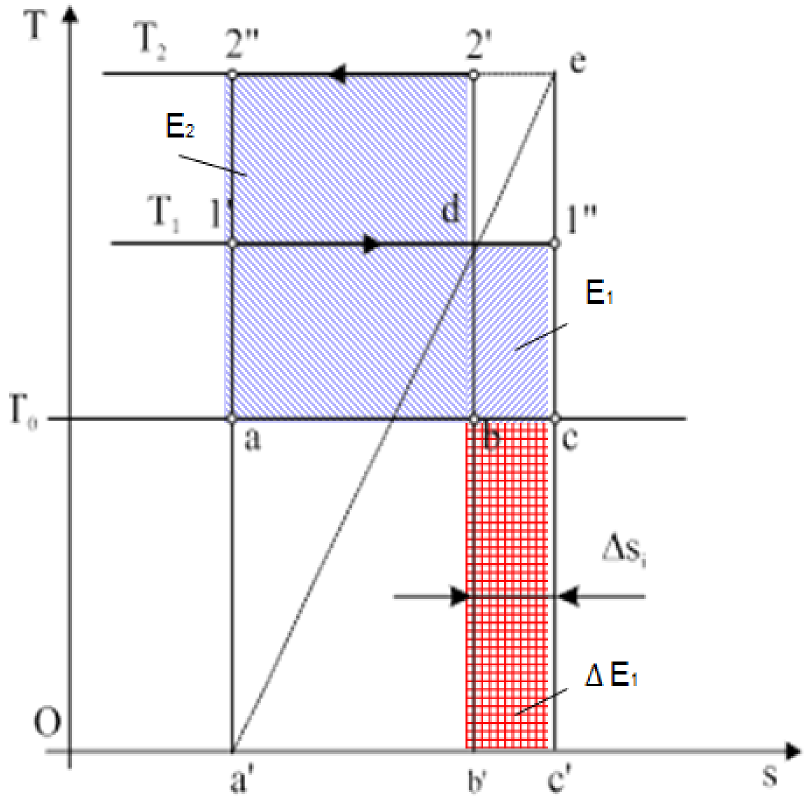

Figure 4. *T-s* diagram of heat exchange of the same substance flows at $T_2 > T_1 > T_0$

4. New graphical approach

For this approach, we can use the same logic applied in the second approach. If the heat taken from 1 kg of the substance of flow 2 (surface 2'2"a'b') is shown as the sum of exergy and anergy,

$$Q_2 = E_2 + A_2 \tag{6}$$

it follows that the surface 2'2"a'b" is equal to the sum of the surfaces 2'2"ab plus the surface of abb'a' where the heat anergy is equal to the surface of abb'a' = A_2. Anergy is a part of the heat energy that can not be converted into work and which is passed on to the environment. In analogy, the heat received by 1 kg of flow 1 (surface 1'1"c'a") can be represented as the sum of exergy and anergy, and consequently the heat anergy is equal to the acc'a' surface = A_1.

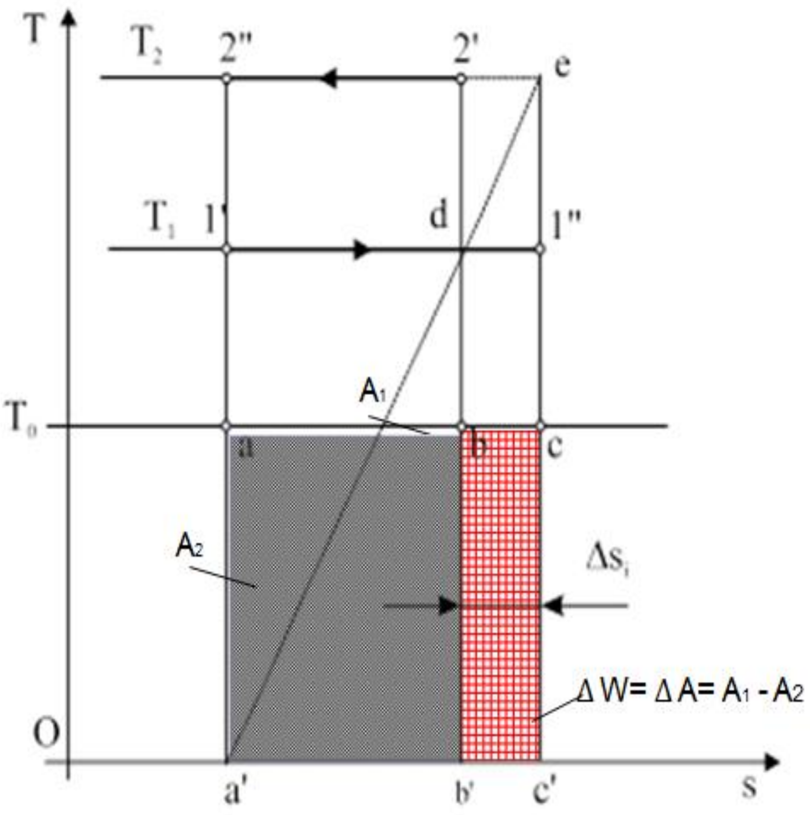

Figure 5. New graphical approach: *T-s* diagram of heat exchange of the same substance flows at $T_2 > T_1 > T_0$

As work loss due to irreversibility can be expressed as difference between the exergy input and output exergy, it follows that:

$$\Delta E = \Sigma E_u - \Sigma E_i = E_2 - E_1 \tag{7}$$

Exergy can be written as:

$$E_1 = Q_1 - A_1 \tag{8}$$

$$E_2 = Q_2 - A_2. \tag{9}$$

So it follows that:

$$\Delta E = Q_2 - A_2 - (Q_1 - A_1). \tag{10}$$

Work loss i.e. exergy loss can be written using anergy:

$$\Delta E = \Delta W = A_1 - A_2 \tag{11}$$

When some amount of heat (equal to the sum of its exergy and anergy) passes from a higher to a lower temperature level, then its exergy decreases and anergy increases. The difference in the heat anergy of the lower and higher temperature levels (after and before the process) is equal to the loss of work (exergy) due to the irreversibility of the process.

This follows that:

$$\Delta E = A_1 - A_2 = T_0 \Delta S_S \quad (12)$$

which is in T-s diagram (Figure 5) the surface acc'a'=A_1 minus the surface abb'a'=A_2. If we use Gouy – Stodola rule that is the product of the ambient temperature and the increase in the entropy of the system.

In both areas, under and above of ambient temperature, work loss due to irreversibility in heat exchange with temperature differences, it can be determined analytically by the expression:

$$\Delta W = T_0 \frac{T_2 - T_1}{T_1 T_2} Q \quad (13)$$

Showing exchange of heat in graphical methods given in Figures 4and 5 provides comprehensive interpretation of this phenomenon. By bringing closer temperatures T_2 and T_1 to the absolute zero, losses of work are inclined to infinity.

5. Conclusion

Some natural phenomena can be defined by different approaches. Today in thermodynamics we use different definitions of second law: Carno, Clausius and Thomson. This is almost possible with analysis of work loss due to irreversibility. So far, there is the Gouy - Stodol's rule ($\Delta E = T_o \Delta S_s$), then graphic interpretation of Gouy - Stodol's rule which has been published in [18], and in this paper is presented the new graphic method. Gouy - Stodo 's rule is presented through the difference of anergy, before and after the process ($\Delta E = A_1 - A_2$) when the heat exchange is in the temperature range above ambient temperature. In fact, it is a slightly simpler approach than the approach presented [18]. In the temperature range below the ambient temperature, the graphical approach presented in [18], it can not be simplified with an exposed logic as it has been done for a temperature range above the ambient temperature. In both areas, under and above of ambient temperature, work loss due to irreversibility in heat exchange with temperature differences, it can be determined analytically (13).

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