EXERGY ANALYSIS: A NEW WAY OF ANALYZING THE ENGINEERING PROCESSES

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ABSTRACT: *The objective of this paper is to emphasize the importance of exergy analysis of a system and its potential benefits. To clarify the point, different heat engine cycles are analyzed using exergy analysis and energy (or first law) analysis and the two are then compared. This study also present the relation between environment and exergy sustainable development and ecology. Exergy is sustainable than the energy because the difference in the energy qualities can be measured if the exergy for the system is calculated, exergy is a key tool for the environment. The efficiency, uses, significance and performance of exergy to integrate the system and describe a variety of system especially for environmental condition is also discussed. This study also take into account exergy concept and demonstrate its use extensively to describe a variety of systems in particular for built environmental conditioning. It is easier to perform and integrate the environment by using exergy. Exergy methods can also be used to increase sustainability. The study of such a comparison will help us to appreciate the importance and productivity of exergy analysis of a system.*

Keywords: Exergy, Exergy analysis, Environmental Impact, Thermodynamic

INTRODUCTION:

All of us are familiar with the terms energy and work and we regularly come across them in our daily routine work. Scientifically, energy is defined as ability of a body to do work. And work is defined usually through its mathematical definition as the product of force and displacement covered under the action of the force. Work is also defined as energy in transition. Work is hence the mechanism by which energy is transferred from a system to its surroundings. Another mechanism for this transfer is 'heat exchange'. First law of thermodynamics governs the transfer of energy from system to its surroundings. Law states that energy can never be created nor destroyed. It is only converted from one form into another. In our everyday conversation, people often claim that energy is consumed not only to express their feelings after a tiresome day at work but also in the scientific discussions regarding work and energy. This seems to be a clear violation of the first law of thermodynamics stated above as the law rules out the possibility of loss or destruction of energy. At the same time it is our common observation that when a fuel has burnt, its energy is no more available to be utilized again and again. Similarly, we believe that gases contained in the atmosphere around us contain enormous amount of internal energy (as their molecules are in a state of continuous motion) but this energy cannot be converted into work. This discussion shows that there is some type of qualitative factor associated with energy and the first law is silent about it. The energy from the fossil fuels is not 'consumed' but 'degraded' and is no more 'available' to be converted into work. To clarify that what is actually 'consumed' we define a new term called exergy.

Authors conducted a study, and presented a novel approach of resource efficiency analysis for factory that was based on the exergy and factory is considered as an integrated system. Authors resented a case study that demonstrated the application of this approach and the different examples for factory energy systems. And illustrated that the exergy destruction is reduced to 50% and up to the 63.2% reduction can be observed for non-renewable energy supply [1]. Duflou et al. (2012) presented the review methods used in the discrete part manufacturing for the improvements of efficiency resources.. This manufacturing system contains some extra systems than the factory. Shows a more holistic approach this approach determines the better opportunities that the resources are reuse. So that the analysis influences the resource efficiency and waste reduction [2]. Technology influences the environment. Rosen (2009) presented theoretical studies and presented different methods and analysis that how exergy analysis to analyze the influence of technology on the environment [3]. Exergy can be used to measure the sustainability of industries Boroum and Jazi et al. (2013) and Sciubba and Wall (2010). Presented the studies and presented the methods that how the industrial sustainability can be measure at any scale.at which scale the exergy analysis is suitable in the manufacturing and especially for the application of material and energy flows with the building services and processes of the factory. This analysis can also be used to explore some benefits compare to the traditional approach of energy balance and mass [4,5]. A study was conducted to discuss the exergy concept and its uses in different systems in especially for environmental conditions by using exergy analysis system can perform easier and can integrate the environment, it can also be used to solve the environmental issues. Exergy method can offer some improvements and emphasis on the sustainability of the environment. It describes many strategies to reduce their influence on the environment. Exergy is the property of the eco system it can be applied to the ecological processes [6].

Similarly authors also reported that exergy can identify better benefits and economics of energy technologies than the environmental. Exergy plays a vital role in increasing the use of green energy and technologies [7]. Exergy is property that is the measure of the leaving off from the system to the environment. Therefore; exergy can generate the connection between the environmental impact and 2nd law of thermodynamics [8]. Sadi Carnot (1796-1832), a French Physicist, was the first person to study the quality of energy. Through his theory and mathematical work, he gave an insight to the conditions under which energy can be converted into work and set an upper bound for the performance of all heat engines. This was the first time when quality of energy came under discussion. In 1873, Josiah Willard Gibbs described physics related to the ‘available energy’ of a body and medium. His mathematical formulations regarding ‘available energy’ have hardly changed since then [9]. Rudolph Clausius (1822-1888) and Lord Kelvin (1824-1907) formulated the results of Carnot in the form of a law known as second law of thermodynamics. Law as stated by Kelvin is, it is impossible to convert heat into work in a cyclic process [9]. Law governs the fact that heat to work conversion in a reversible cycle always follows a heat transfer. The heat transfers from a hot reservoir to the colder one. An amount of heat is lost during heat to work conversion process. Also work can be converted into heat completely and continuously. Clausius stated that heat generally cannot move from a material at low temperature to a material at high temperature [9]. His statement governs the process of refrigeration and the working of heat pumps.

EXERGY:

The exergy of a system is generally defined as the maximum work that has been done during a process that maintains the system into equilibrium with an environment [9]. It is measured in joules. The system will deliver the maximum possible work when it undergoes a reversible process from the specified initial state to the state of environment (state of environment is referred to as ‘dead state’. This is the amount of useful work a system can deliver under the given conditions of system as well as environment. This maximum possible work is called exergy of the system [10]. Hence exergy is dependent on the condition of both the system and the surroundings (environment) and it is not a state property of a system. In simpler words, exergy is the availability of energy in a system to be converted into work. In this way exergy gives us the qualitative measure of energy contained in a system as compared with its environment. It is worth noting here that this quality can be enhanced by changing the state of system as well as the surroundings (environment). Moreover, it is not for sure that all the exergy (available energy) is converted by a system into work. Exergy only puts an upper bound on the energy that can be converted into work. Irreversibility in a system can cause of ‘loss of exergy’ which limits the output of system. As stated earlier that exergy is the measure of maximum possible work that can be extracted from an energy resource, to calculate exergy we have to calculate the work that can be extracted. Suppose a body of mass ‘m’ is moving with a velocity ‘v’. It will have a kinetic energy of $\frac{1}{2}\mathrm{mv}^2$. It is possible to reduce the velocity of the body to zero. And when it is done the body will lose all its kinetic energy. If this decrease in velocity is carried out in a turbine or wind mill then this energy is available to be converted into work hence exergy associated with kinetic energy possessed by a body is given by, $\mathrm{X} = \frac{1}{2}\mathrm{mv}^2$. As all the energy has been converted into work, the exergy of system in final state is zero.

Similarly if a body of mass ‘m’ is raised to a certain height ‘h’ from an arbitrary reference point in a gravitational field of acceleration ‘g’ then energy stored in the body will be mgh. If the body is allowed to fall from that height to the reference line such that ‘h’ is reduced to zero, all the potential energy possessed by the body is converted to other forms. This energy can also be converted into useful work by using appropriate machine (turbine, hydraulic accumulator etc.). Hence exergy associated with gravitational potential energy is given by $\mathrm{X} = \mathrm{mgh}$. As all the energy has been converted into work, the exergy associated with gravitational potential energy of system in final state is again zero.

Now we discuss the concepts which are purely related to thermodynamics. Consider a hot reservoir at a temperature ’T’ as shown in the Figure 1. Environment surrounding the reservoir is at temperature ‘$\mathrm{T_o}$’.

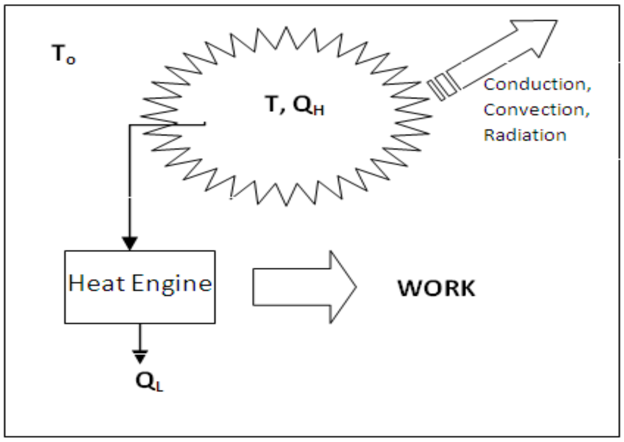

Figure 1: Directional Flow of Heat and Work

As shown in the fig (1) the reservoir contains heat $\mathrm{Q_H}$. According to Carnot’s theorem, if a heat engine is operated between this reservoir and the surrounding environment then the maximum heat engine efficiency will be, $\eta = 1 - \frac{\mathrm{T_o}}{\mathrm{T}}$. We know that efficiency is defined as $\eta = \frac{\text{Net Work output}}{\text{Heat Input}}$. Hence the possible work output will be $\mathrm{W} = \mathrm{Q_H}\left(1 - \frac{\mathrm{T_0}}{\mathrm{T}}\right)$. As exergy is measure of maximum possible work output, so

$$\mathrm{X} = \mathrm{Q_H}\left(1 - \frac{\mathrm{T_0}}{\mathrm{T}}\right)$$

Thermodynamic System – An Exergy-Entropy System:

Working of a thermodynamic system can be explained as the working of an exergy-entropy system [3]. This approach helps us to identify the inter relationship of the concepts of exergy, entropy and energy. Entropy is defined as a measure of the unavailability of a system’s energy to do work; also a measure of disorder; the higher the entropy the greater the disorder [11]. Consider the fig (1) again where a heat engine is operated between a heat source and environment. The heat input of the system equal to the total energy input is $\mathrm{Q_H}$, and the output is $\mathrm{Q_L}$. An energy balance equation for the system neglecting the gravitational potential energy and kinetic energy, we have,

$$\mathrm{Q_H} = \mathrm{W} + \mathrm{Q_L} + \Delta\mathrm{U} \qquad (1)$$

As system returns to its initial state so $\Delta\mathrm{U} = 0$. Now we write an entropy balance equation for the same system i.e. heat engine.

$$\mathrm{S_H} + \mathrm{S_{gen.}} = \mathrm{S_L} + \Delta\mathrm{S} \qquad (2)$$

Here, S_H is the entropy associated with heat input. S_L is the entropy associated with the heat rejected and S_{gen} is the entropy generated in the system due to irreversibility. As the system returns to its original state hence $\Delta S = 0$ in this case. Multiplying (2) by T_o which is the environment temperature and subtracting from (1).

$$(Q_H - S_H T_o) - S_{gen.} T_o = (Q_L - S_L T_o) + W \qquad (3)$$

From the definition of entropy it is quite clear that the terms$S_H T_o$, $S_{gen.} T_o$, $S_L T_o$, having dimensions of energy, represent that part of energy which is unavailable to be transformed into work. And the difference of these terms from the heat inputs and outputs represent exergy i.e.

$$Q_H - S_H T_o = X_H$$
$$Q_L - S_L T_o = X_L$$

Equation (3) now becomes:

$$X_H - S_{gen.} T_o = X_L + W \qquad (4)$$

X_L is the exergy contained in the heat rejected. As the heat rejected in our example is at the temperature of the environment so it does not contain any exergy and this term is also zero. In this equation the term’ $S_{gen.} T_o$ arises due to irreversibility is referred to as exergy destroyed i.e. $X_{des.} = S_{gen.} T_o$. This is the amount of energy that was initially available for conversion into work but was wasted due to friction and other causes of irreversibility (heat transfer due to finite temperature difference or work transfer due to finite pressure difference). The final equation we thus have is as follows:

$$X_H - X_{des.} = W$$

If all the processes in the engine are completely reversible then $X_{des.} = 0$ and all the exergy input is converted into work by the system.

Exergy Efficiency:

We reconsider a simple heat engine as we illustrated earlier (consider fig. 1). Thermal efficiency of the system is simply calculated as

$$\eta_{th} = \frac{W_{net,out}}{Q_H} \qquad (1)$$

Where heat supplied can be calculated as:

$Q_H = m \times (\text{calorific value})$.

This value will give us the amount of heat supplied by burning ‘m’ mass of fuel.

The efficiency is defined as the work output divided by the exergy input. This value of efficiency is known as exergy efficiency or the 2nd law efficiency. Mathematically,

$$\eta_{ex} = \frac{W_{net,out}}{X_H} \qquad (2)$$

As stated earlier the exergy associated with a particular heat input Q_H is given as $X_H = Q_H\left(1 - \frac{T_o}{T}\right)$. We have the relation for exergy efficiency as:

$$\eta_{ex} = \frac{W_{net,out}}{Q_H\left(1 - \frac{T_o}{T}\right)} \qquad (3)$$

This efficiency describes that how much the available work has been converted into work. This efficiency is called as second law efficiency as it uses the concepts of second law to evaluate performance of a system.

Illustrative example:

We consider example of a petrol engine to illustrate the concept of exergy efficiency and its comparison with the first law efficiency. During an operation of one minute, the engine produces a total work of 11.19 MJ. During this period, the total heat supplied is 31.97 MJ [12]. To determine exergy input of the heat supplied, we need to know the source and sink temperature. We assume that heat is supplied at a temperature of 1000 K and rejected at a temperature of 288 K (these assumptions lie in the range of normal working conditions). We calculate the first law efficiency using (1) and second law efficiency using (3).

$$\eta_{th} = \frac{11.19}{31.97} = 35\%$$

$$\eta_{ex} = \frac{11.19}{31.97\left(1 - \frac{288}{1000}\right)} = 49\%$$

Thermal efficiency is very low as compared to the exergy efficiency. But the exergy efficiency actually gives the quantitative measure of engine’s performance. As 29% of the heat input (Q_L = 9.27 MJ) was never available to be converted into work so it is not inefficiency of the engine that this energy is wasted For an engine in which all the processes are completely reversible, exergy efficiency is equal to 100%. Exergy efficiency is the measure of approximation to reversible operation and its value should be zero in worst case (when all the work potential- exergy is destroyed) to one (in a completely reversible process with no loss of exergy) [13].

Other examples:

Exergy is a very important analysis tool not only for heat engines but for all sort of thermodynamic systems. It can be applied even to different phenomena of daily life which are not technical in nature.

Consider for example an electric room heater whose manufacturer claims that it has an efficiency of 100% i.e. for each unit of electrical energy consumed the heater supplies the room with one unit of heat. Clearly the heater has a first law efficiency of 100%. Now we calculate second law efficiency for the same heater. Coefficient of performance (COP) of a device is defined as:

$$COP = \frac{1}{1 - {T_L}/{T_H}}$$

Assuming an indoor temperature of 21°C (T_H = 294 K) and outdoor temperature of 10°C (T_L = 283 K)-common winter conditions, the COP comes out to be 26.7, which implies that if a heat pump is used to heat the room, it will supply 26.7 times heat to the room (extracted from outdoors). The work potential of this electrical energy supplied will be 26.7 units for each unit of electrical energy supplied. Exergy efficiency of the heater (using (2) from section 2.2) comes out to be $\eta'_{ex} = \frac{1}{26.7} = 3.7\ \%$. Hence when the actual work potential is taken in to account we observe that the heater is wasting 96.3% of the available work potential and a heat pump proves to be a better alternative [14].

The best example for the exergy analysis application in our daily life id consider a fresh student who want to spend his next three hours for studying a book and watch a two hour long movie [14]. It is clear that if he watches movie first and then study. So he will not get quite results as he has wasted much of his consideration in watching the movie. And cannot gain from study. If he study first then he watches movies so he will be able to get more knowledge from study in less period of time and then enjoy the movie, as movie require less attention.

Significance of Exergy Analysis:

Scientists from round the world have bowed to the supremacy of 2nd law of thermodynamics. Ivan P. Bazarov, author of "Thermodynamics" (1964) wrote: “The second law of thermodynamics is, without a doubt one of the most perfect laws in physics.”

Thermodynamic systems are best evaluated and improved by carrying out the exergy analysis in addition to or, altogether, in place of energy analysis [15].

Exergy has different features, The first aspect of the "exergy" is that it is the possibility to compare the inputs and out puts on common basis that are different in the physical analysis. Further it can also be estimated that in the consideration of exergy streams it is the possibility to measure the exergy that system destroys [16].

Exergy analysis can also be used to determine the losses and their causes and locations in a thermodynamic system and improve the overall system and its components. It is also directly related to sustainability and environment. By increasing the exergy efficiency of the syste, sustainability increases and environmental influences decreases. A major portion of the exergy is converted from one useful form to another and no available work is lost to the environment as entropy [17].

CONCLUSION:

Over the past few decades, exergy analysis and efficiency has received widespread recognition on all levels-research and industrial application alike. Work can continuously and completely be converted to other forms of work. This is not possible for in the case of heat. Since it is the ability of work that gives energy its due importance, analysis must be aimed for the measurement and conservation of the available work and not on energy. By focusing research on thermodynamic systems and processes having the lowest value of exergy efficiencies, progress can be achieved in area that have the largest scope for efficiency improvement. Contrary to this, focusing on energy efficiencies alone can lead to wastage of time and other resources for the sake of areas that have very little if not altogether zero margins for improvement.

However, it must be added that energy considerations may not be ignored altogether. They have their own place in the study of thermodynamic systems and there are cases where it is feasible to compromise exergy and rely on energy analysis alone. For example the installation and working of a heat exchanger. Trying to increase exergy efficiency by limiting the temperature range may prove to be very expensive and not practically possible. In fact, the best approach is not to derive conclusions exclusively on the results drawn from the study of exergy and energy but to take into consideration other factors like economics, environments and social implications as well.

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