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Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering

Santosh V Kadam[1] and Sarika Khare[2]

Workshop Superintendent, Bharati Vidyapeeth Institute of Technology, Navi Mumbai, India[1]

Lecturer, Bharati Vidyapeeth Institute of Technology, Navi Mumbai, India[2]

Abstract: *Energy, entropy and exergy concepts come from thermodynamics and are applicable to all fields of science and engineering. Therefore, this article intends to provide background for better understanding of these concepts and their differences among various classes of life support systems with a diverse coverage. It also covers the basic principles, general definitions and practical applications and implications. Some illustrative examples are presented to highlight the importance of the aspects of energy, entropy and exergy and their roles in thermal engineering.*

Keywords: Energy, entropy, environment, exergy, thermodynamics

I. INTRODUCTION

Thermodynamics is broadly viewed as the science of energy, and thermal engineering is concerned with making the best use of available energy resources. The name thermodynamics stems from the Greek words therme (heat) and dynamics (force), which is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations, including power production, refrigeration, and relationships among the properties of matter.

The science of thermodynamics is built primarily on two fundamental natural laws, known as the first and the second laws. The first law of thermodynamics is simply an expression of the conservation of energy principle. It asserts that energy is a thermodynamic property, and that during an interaction,energy can change from one form to another but the total amount of energy remains constant. The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. The high-temperature thermal energy is degraded as it is transferred to a lower temperature body. The attempts to quantify the quality or "work potential" of energy in the light of the second law of thermodynamics has resulted in the definition of the properties entropy and exergy.

The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of William Rankine, Rudolph Clausius, and William Thomson (later Lord Kelvin). Although the principles of thermodynamics have been in existence since the creation of the universe, thermodynamics did not emerge as a science until the construction of the first successful atmospheric steam engines in England by Thomas Savery in 1697 and Thomas Newcomen in 1712. These engines were very slow and inefficient, but they opened the way for the development of a new science.

The scope of this article is partly illustrated in Fig. 1, where the domains of energy, entropy and exergy are shown. This paper focuses on the portion of the field of thermodynamics that intersects with the energy, entropy and exergy fields, and particularly emphasizes the intersection of all three domains. Note that entropy and exergy are also used in other fields (such as statistics and information theory), and therefore they are not subsets of energy. Also, some forms of energy (such as shaft work) are entropy-free, and thus entropy subtends only part of the energy field. Likewise, exergy subtends only part of the energy field as well since some systems (such as air at atmospheric conditions) possess energy but no exergy. Most thermodynamic systems (such as steam in a power plant) possess energy, entropy, and exergy, and thus appear at the intersection of these three fields.

II. ENERGY

2.1 Introduction

Thermodynamics plays a key role in the analysis of systems and devices in which energy transfer and energy transformation take place. Thermodynamics' implications are far-reaching, and its applications span the whole range of the human enterprise. All along our technological history, the development of sciences has enhanced our ability to harness energy and use it for society's needs. The industrial revolution is a result of the discovery of how to exploit energy and how to convert heat into work. Nature allows the conversion of work completely into heat, but heat is taxed when converted into work. For this reason, the return on our investment of heat transfer is compared with the output work transfer and attempts are made to maximize this return.

Most of our daily activities involve energy transfer and energy change. The human body is a familiar example of a biological system in which the chemical energy of the food or body fat is transformed into other forms of energy such as heat transfer and work transfer. Our encounter with the environment also reveals a wide area of engineering applications. These include power plants to generate electricity, engines to run automobiles and aircraft, refrigeration and air conditioning systems, and so on.

2.2 Concept of Energy

The concept of energy was first introduced in mechanics by Newton when he hypothesized about kinetic and potential energies. However, the emergence of energy as a unifying concept in physics was not adopted until the middle of the 19th century and was considered one of the major scientific achievements in that century. The concept of energy is so familiar to us today that it is intuitively obvious, yet we have difficulty in defining it exactly. Energy is a scalar quantity that can not be observed directly but can be recorded and evaluated by indirect measurements. The absolute value of energy of system is difficult to measure, whereas its energy change is rather easy to calculate. In our life the examples for energy are endless. The sun is the major source of the earth's energy. It emits a spectrum of energy that travels across space as electromagnetic radiation. Energy is also associated with the structure of matter and can be released by chemical and atomic reactions. Throughout history, the emergence of civilizations has been characterized by the discovery and effective application of energy to society's needs.

2.3 Forms of Energy

Energy manifests itself in many forms, which are either internal or transient, and energy can be converted from one form to another. In thermodynamic analysis, the forms of energy can be classified into two groups:

- **The macroscopic forms of energy** are those where a system possesses as a whole with respect to some outside reference frame such as kinetic and potential energies. For example, the macroscopic energy of an upmoving object changes with velocity and elevation. The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity and surface tension. The energy that a system possesses as a result of its motion relative to some reference frame is called kinetic energy. The energy that a system has as a result of its elevation in a gravitational field is called potential energy.
- **The microscopic forms of energy** are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the internal energy of a system. The internal energy of a system depends on the inherent qualities, or properties, of the materials in the system, such as composition and physical form, as well as the environmental variables (temperature, pressure, electric field, magnetic field, etc.). Internal energy can have many forms, including, sensible and latent (i.e., thermal), chemical, nuclear, electrical, mechanical, magnetic, and surface energy.

2.4 The First law of Thermodynamics (FLT)

The FLT stands for the first law of the conservation of energy. This is stated as energy can be neither created nor destroyed; it just changes form. The FLT defines internal energy as a state function and provides a formal statement of the conservation of energy. However, it provides no information about the direction in which processes can spontaneously occur, that is, the reversibility aspects of thermodynamic processes. For example, it cannot say how cells can perform work while existing in an isothermal environment. It gives no information about the inability of any thermodynamic process to convert heat into mechanical work with full efficiency, or any insight into why mixtures cannot spontaneously separate or unmix themselves. An experimentally derived principle to characterize the availability of energy is required to do this. This is precisely the role of the second law of thermodynamics that we will explain later.

2.5 FLT vs Energy

The total energy E represents the sum of all forms of energy a system possesses, and the change in the energy content of a system during a process is expressed as ΔEsystem . In the absence of electrical, magnetic, surface, etc effects, the total energy in that case can be expressed as the sum of the internal, kinetic, and potential energies as

$E = U + KE + PE$ and $\Delta E_{system} = \Delta U + \Delta KE + \Delta PE$

III. ENTROPY

3.1 Introduction

Within the past 50 years our view of Nature has changed drastically. Classical science emphasized equilibrium and stability. Now we see fluctuations, instability, evolutionary processes on all levels from chemistry and biology to cosmology. Everywhere we observe irreversible processes in which time symmetry is broken. The distinction between reversible and irreversible processes was first introduced in thermodynamics through the concept of "entropy".

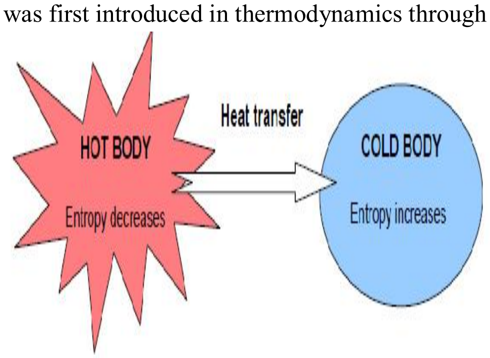

Fig 1 Illustration of entropy increase and decrease for cold and hot bodies.

3.2 Entropy Aspects

It is now important to introduce a new thermodynamic property, entropy, that is simply a measure of the amount of molecular disorder within a system. In this regard, a system possessing a high degree of molecular disorder (such as a high temperature gas) has a very high entropy value and vice versa. It is important to note that numerical values for specific entropy are commonly listed in thermodynamic tables along with values for specific volume, specific internal energy, and specific enthalpy. Therefore, entropy is known as the core of the second law thermodynamics. Here, we have to highlight the following facts:

- The entropy of a system is a measure of the amount of molecular disorder within the system.+
- A system can only generate, not destroy, entropy.
- The entropy of a system can be increased or decreased by energy transports across the system boundary.

3.3 Significance of Entropy

The "entropy" of the state of a system is a measure of the probability of its occurrence. States of low probability have low entropy; states of high probability have high entropy. With this definition we see, from the previous discussion and examples, that in any transfer or conversion of energy, because the spontaneous direction of the change of state of a closed system is from a less to a more probable state, the entropy of the system must increase. That is the broader statement we have been seeking for the second law, "In any energy transfer or conversion within an isolated closed system, the entropy of that system increases."

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Energy conversions can proceed so that the entropy of a part of a system is decreased. Charging a storage battery, freezing ice cubes, and even the processes of life and growth are examples. In each of these examples, order has been won from disorder and entropy has decreased. If the total system is considered, however, the total effect has been an increase in disorder. To charge a battery we must provide energy above and beyond that necessary to re-form the chemical combinations in the battery plates. Some of this low-entropy electrical energy is changed into high-entropy heat energy in the current-carrying wires. In freezing ice we increase the order and thus decrease the entropy of the water in the ice cube trays by removing heat from it. The heat energy removed, however, has to flow into a substance that is at a lower temperature than the surroundings. Thus, the entropy and the disorder of this gas are increased. Moreover, we put low-entropy electrical energy into the refrigerator through the motor, and this energy is degraded to heat. The overall change in entropy is positive. In the life process, highly ordered structures are built from the much simpler structures of various chemicals, but to accomplish this, life takes in relatively low-entropy energy-sunlight and chemical energy-and gives off high-entropy heat energy. The entropy of the total system again increases.

3.5 The Second Law of Thermodynamics (SLT)

Although a spontaneous process can proceed only in a definite direction, the FLT gives no information about direction; it merely states that when one form of energy is converted into another, identical quantities of energy are involved regardless of feasibility of the process. In this regard, events could be envisioned that would not violate the FLT, e.g., transfer of a certain quantity of heat from a low temperature body to a high-temperature body, without expenditure of work. However, the reality shows that this is impossible and FLT becomes inadequate in picturizing the complete energy transfer. Furthermore, experiments indicated that when energy in the form of heat is transferred to a system, only a portion of heat can be converted into work.

3.6 SLT Statements

Although there are various formulations of the SLT, two of them are better known such as the Clausius statement and the Kelvin-Planck statement.

- The Clausius statement. It is impossible for a system to transfer heat from a lower temperature reservoir to a higher temperature reservoir. Simply, heat transfer can only occur spontaneously in the direction of temperature decrease. For example, we cannot construct a refrigerator that operates without any work input.
- The Kelvin-Planck statement. It is impossible for a system to receive a given amount of heat from a high-temperature reservoir and provide an equal amount of work output. While a system converting work to an equivalent energy transfer as heat is possible, a device converting heat to an equivalent energy transfer as work is impossible. For example, we cannot build a heat engine that has a thermal efficiency of 100%

3.8 Useful Relationships

It is important to list some useful relations and Tds equations for any process of a pure substance, assuming the absence of electricity, magnetism, solid distortion effects, and surface tension. Therefore, we list four equations and highlight their implications and restrictions as follows:+

- $\delta q = du + \delta w$: closed system. This is a statement of the FLT and is applicable to any simple compressible
- $\delta q = du + pdv$: This is a statement of the FLT and is restricted to reversible processes of a closed system only.
- $Tds = du + \delta w$: This is a combined statement of the FLT and SLT (with $Tds = \delta q$).
- $Tds = du + pdv$: This is a combined statement of the FLT and SLT and is valid for all processes between equilibrium states.

IV. EXERGY

4.1 Introduction

A very important class of problems in engineering thermodynamics concerns systems or substances that can be modelled as being in equilibrium or stable equilibrium, but that are not in mutual stable equilibrium with the surroundings. For example, within the earth there are reserves of fuels that are not in mutual stable equilibrium with the atmosphere and the sea. The requirements of mutual chemical equilibrium are not met. Any system at a temperature above or below that of the environment is not in mutual stable equilibrium with the environment. In this case the requirements of mutual thermal equilibrium are not met. It is found that any lack of mutual stable equilibrium between a system and the environment can be used to produce work. The SLT allows the maximum work that could be produced to be determined.

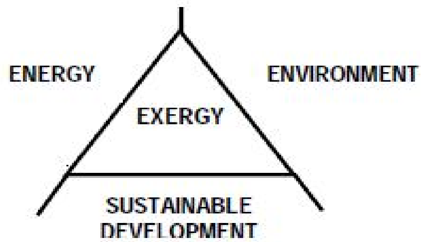

Fig. 2 The interdisciplinary triangle of exergy

4.2 Exergy Aspects

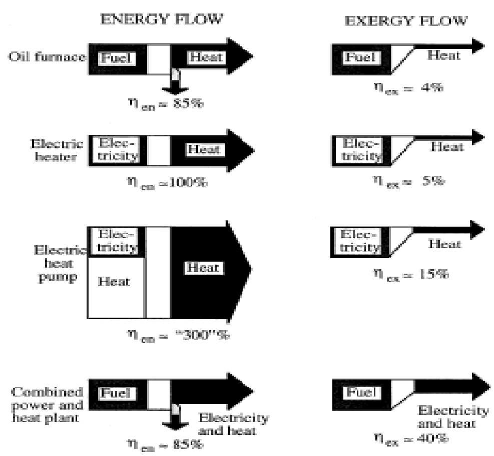

Fig. 3 Energy and exergy efficiency for an oil furnace, an electric heater, an electric heat pump and a combined power and heat plant

It is also important to illustrate some meanings of exergy by the following simple examples:

- A system in complete equilibrium with its environment does not have any exergy. No difference appears in temperature, pressure, or concentration etc. for running any processes.
- The more a system deviates from the environment, the more exergy it carries. Hot water has a higher content of exergy during the winter than it has on a hot summer day. A block of ice carries hardly any exergy in winter while it does in summer.
- When the energy loses its quality, it results in exergy destroyed. The exergy is the part of the energy which is useful in the society and therefore has an economic value and is worth taking care of.
- Almost all energy, converted in the thin layer on the earth's surface, where life can be found, derives from the sun. Sunlight, rich in exergy, reaches the earth. A lot of it is reflected but the energy absorbed on the earth is converted and finally leaves the earth as heat radiation with no exergy relative to the earth. The net exergy absorbed by the earth is consequently gradually destroyed but during this destruction it manages to drive the water/wind system and the life on earth. The green plants absorb exergy from the sunlight and convert it via photosynthesis into chemical exergy. The chemical exergy then passes through different food chains in the ecosystems. On every tropical level exergy is consumed and micro-organisms live on the last level in this food chain. There exists no waste.

4.3 Exergy vs Energy

The traditional method of assessing the energy disposition of an operation involving the physical or chemical processing of materials and products with accompanying transfer and/or transformation of energy is by the completion of an energy balance. This balance is apparently based on the FLT. In this balance, information on the system is employed to attempt to reduce heat losses or enhance heat recovery. However, from such a balance no information is available on the degradation of energy, occurring in the process and to quantify the usefulness or quality of the heat content in various streams leaving the process as products, wastes, or coolants.

The exergy method of analysis overcomes the limitations of the FLT. The concept of exergy is based on both FLT and SLT. Exergy analysis can clearly indicate the locations of energy degradation in a process that may lead to improved operation or technology. It can also quantify the quality of heat in a reject stream. So, the main aim of exergy analysis is to identify the causes and to calculate the true magnitudes of exergy losses.

V. CONCLUSION

In a broader perspective (except for the zeroth and third law of thermodynamics), we can define the thermodynamics as a science of energy, exergy, and entropy. Apparently, the FLT refers to the energy analysis which only identifies losses of work and potential improvements or the effective use of resources, e.g., in an adiabatic throttling process. However, the SLT, i.e., exergy analysis takes the entropy portion into consideration by including irreversibilities. During the past decade exergy related studies have received considerable attention from various disciplines ranging from chemical engineering to mechanical engineering, from environmental engineering to ecology and so on. As a consequence of this, recently, international exergy community has expanded greatly