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# Influence of thermodynamics on the development of technology and science

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## Abstract

Understanding thermodynamics can be challenging due to its dealing with abstract concepts such as entropy and energy transfer. This paper outlines six principles of thermodynamics, whose application necessitates a coherent overarching philosophy. The problems studied often entail complex mathematical equations, relying on a strong foundation in physics and mathematics. Moreover, comprehending thermodynamics requires a shift in thinking, focusing on macroscopic properties of matter rather than microscopic interactions, as in other branches of physics. Thermodynamics also introduces a new philosophy in science – the concept of irreversible phenomena, rooted in the heat flow theory, which is currently being extrapolated to other scientific domains. Notably, this involves extending the concept of work to systems performing various types of work beyond volume change.

**Keywords:** Thermodynamics; Civilization; Energy; Entropy; Technology; Science

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## 1. Introduction

Thermodynamics, as a physical science, accounts for the transformations of energy in the form of thermal energy (heat) into mechanical energy and its equivalent forms (work, other forms of energy, and self-organization of complex systems) and vice versa.

The advancement of civilization is closely tied to the escalating demand for energy. The industrial revolution in England at the close of the 18th century was catalyzed, in part, by Watt's invention of the steam engine, leading to a rapid progression in technology and engineering. This invention facilitated the conversion of chemical energy from fuels into mechanical work, enabling the mass production of goods. Steam locomotives and

ships revolutionized transportation, while steam turbines emerged in power plants, followed by gas turbines, facilitating convenient electricity production for various applications.

About half a century after the steam engine's inception, French scientist Sadi Carnot (1796-1832) [1] formulated the Second Law of Thermodynamics (II LT) in his theory of thermal machines. In 1859, French engineer Étienne Lenoir (1822–1900) [2] developed the first internal combustion engine, later improved by Nicolaus Otto in Germany. This development significantly contributed to the understanding of combustion and detonation theories. The rise of transportation driven by internal combustion engines, followed by aircraft engines, led to

## Nomenclature

$a$	– generalized displacement, m
$e$	– unit total energy, J/kg
$G$	– mass velocity, kg/(m <sup>2</sup> s)
$G$	– Gibbs function, J
$h$	– enthalpy, J/kg
$H$	– total enthalpy, J
$I$	– irreversibility, J
$l$	– work, J
$L$	– Onsager coefficients, total work, -, J
$\dot{L}$	– power, J/s
$\dot{m}$	– mass flux, kg/s
$N$	– number of particles
$p$	– pressure, probability of microstate, Pa, -
$q$	– unit heat, J/kg
$\dot{q}$	– heat flux, W/m <sup>2</sup>
$Q$	– heat, J
$\dot{Q}$	– heat rate, J/s
$R$	– individual gas constant, J/(kg K)
$s$	– specific entropy, J/(kg K)
$S$	– total entropy, J/K
$\dot{S}$	– rate of entropy, J/(s K)
$T$	– temperature, K
$u$	– internal energy, J/kg
$v$	– specific volume, kg/m <sup>3</sup>
$V$	– volume, m <sup>3</sup>
$X$	– generalised force, N

## Greek symbols

$\alpha$	– excitation
$\beta$	– excitation
$\Delta$	– difference
$\varepsilon$	– Casimir generalisation coefficients
$\eta$	– thermal efficiency

## Subscripts and Superscripts

$C$	– Carnot cycle
$e$	– change in entropy due to the import of matter from the environment
$i$	– irreversibility of transformations in the system
$in$	– heat input to the system
$isol$	– isolated system
$k$	– kinetic energy
$max$	– maximum
$o$	– reversible process
$p$	– potential energy
$ref$	– reference state
1	– heat introduced to the system
2	– heat removed from the system

## Abbreviations and Acronyms

I LT	– First Law of Thermodynamics
II LT	– Second Law of Thermodynamics

the migration of affluent individuals from urban centres to suburban areas.

The field of thermodynamics, which deals with the conversion of energy into work and heat, was born. Despite its name, it has little to do with dynamics. James Joule [3] was pivotal in establishing the equivalence of work and heat as forms of energy conversion and formulating the principle of energy conservation – the First Law of Thermodynamics (I LT), often referred to as Joule's principle.

This paper aims to introduce an expansion of the concept of work to include systems performing work beyond volume change, and the utilization of thermodynamic principles by modern science, particularly regarding the concept of irreversible states. Presented herein are examples from biology, information technology, and statistics, yet these examples still do not fully explore the capabilities of the tools developed in thermodynamics.

## 2. Classical thermodynamics in physics

Modern thermodynamics transcends being merely a theory of heat machines; it represents a new philosophical paradigm in physics. During the Renaissance era, phenomena were perceived as lacking a temporal direction, with physical laws assumed to be reversible. Pioneers like Galileo Galilei and Isaac Newton did not account for the asymmetry of process changes. Newtonian physics primarily focused on optics, mechanics, and electrostatics. However, by the late 18th and 19th centuries, the theory of heat gained prominence within physics, highlighting the interplay between thermal and mechanical energy. This gave rise to the field of thermodynamics [4-6], which primarily concerns the conversion of energy into work and heat.

Scientists soon realized that not all thermal energy could be entirely converted into mechanical energy, while the reverse conversion was relatively straightforward. Carnot, in his pursuit of maximizing thermal-to-mechanical energy conversion, identified a limit, later formulated by Clausius [7] as the Second Law of Thermodynamics (II LT). This law underscores the qualitative nature of energy, where although the total energy remains constant, its ability to perform work depends on energy parameters. Clausius introduced the concept of 'entropy,' defining it as the quotient of heat and temperature on an absolute scale. The increase in entropy within the universe delineates the direction of time's arrow, with heat and work serving as components of energy balance.

Classical physics and chemistry predominantly deal with closed systems (see Fig. 1), with equilibrium states being a key consideration. Equilibrium, characterized by uniform parameters across the system, is essential for thermodynamic analysis. A system, separated from the rest of the universe by a boundary, contains matter, while the surrounding environment comprises the rest of the universe.

Equilibrium processes, although idealized, do not naturally occur in nature, as systems tend to lose equilibrium during state transitions. However, for practical purposes, it suffices for states to reach equilibrium faster than the system transitions between states, ensuring a relaxation time shorter than the phenomenon's duration. Equations of state, distinguishing between thermal and caloric equations, relate extensive parameters such as specific volume to intensive parameters like pressure and temperature:

$$f(p, v, T) = 0. \quad (1)$$

The similar holds for the caloric equation of state. It can be represented as:

$$e(v, T) = 0, \quad (2)$$

or, using Eq. (1), in alternative forms:

$$e(p, T) = e(p, v) = 0, \quad (3)$$

where the total energy per kilogram substance reads as  $e = E/m$  [kJ/kg], and specific volume  $v = V/m$  [m<sup>3</sup>/kg]. The parameters  $p$ ,  $v$ ,  $T$  are fundamental, easily measurable parameters.

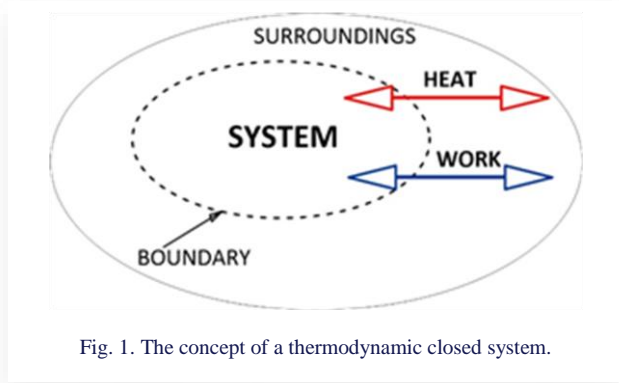


Fig. 1. The concept of a thermodynamic closed system.

Instead of the thermal and energy equations of state, a fundamental equation can be formulated, which contains all the information that the thermal and energy equations of state contain. The parameters of the fundamental equation are the natural equations resulting from the I LT. Let us analyse the internal energy function in intensive coordinates  $u(s, v)$ , for a simple compressible substance

$$e(p, T) = e(p, v) = 0. \quad (4)$$

From the differentiated version of Eq. (4), the thermal and caloric equation for the substance under consideration can be obtained

$$du = \left(\frac{\partial u}{\partial s}\right)_v ds + \left(\frac{\partial u}{\partial v}\right)_s dv. \quad (5)$$

In Eq. (5), comparing the first term on the right with the I LT notation gives the definition of temperature and the second term on the right has the dimension of pressure:

$$T = \left(\frac{\partial u}{\partial s}\right)_v = f_1(s, v), \quad (6)$$

$$p = -\left(\frac{\partial u}{\partial v}\right)_s = f_2(s, v). \quad (7)$$

Eliminating the entropy  $s$  from the above relationships, one obtains the thermal equation of state  $f(p, v, T) = 0$ . Conversely, substituting into Eq. (4) the entropy value from either function  $f_1$ , eq. (6), or  $f_2$  eq. (7), one obtains the caloric equation of state. The thermal and caloric equations of state can be encapsulated in a fundamental equation, which encompasses all pertinent information from these individual equations. This fundamental equation, often represented by the internal energy function  $u(s, v)$  for a simple compressible substance, provides insights into both thermal and caloric equations of state. Additionally, it

facilitates the derivation of other thermodynamic functions through Legendre transformations.

For a simple system, the equilibrium states, depicted in Fig. 2, are characterized by nodes on the state surface. These equilibrium transitions give rise to various processes, such as isochoric, isobaric, and isothermal processes, forming a thermodynamic cycle.

The laws governing thermodynamics are written as its principles. The I LT is the principle that formulates the energy balance valid for both reversible and irreversible transformations of parameters of the system (Accountant's Principle). The change in energy of a closed system is due to the work done and the heat transferred. For closed systems for which external energy changes during the transformation can be neglected, the I LT can be written in the form:

$$\delta q = du + \delta l, \quad (8)$$

where  $\delta l = pdv$ .

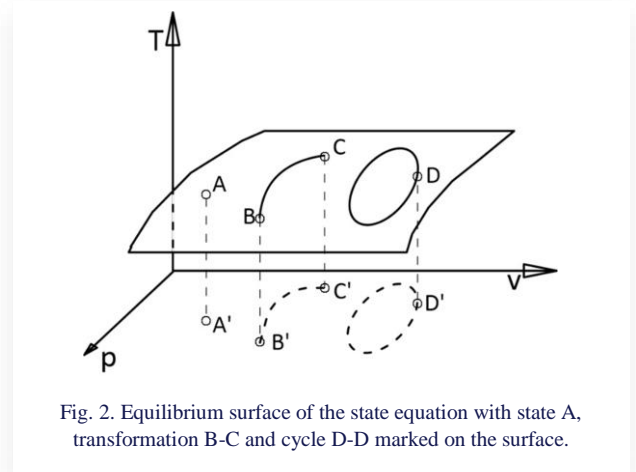


Fig. 2. Equilibrium surface of the state equation with state A, transformation B-C and cycle D-D marked on the surface.

I LT is sometimes referred to as the energy principle because it formulates the internal energy. In order to simplify thermodynamic calculations of thermal devices, another thermodynamic function, the enthalpy  $h$ , is introduced. This function was first introduced by Gibbs and reads:

$$h = u + pv. \quad (9)$$

Enthalpy is a function of state, similar as internal energy as well as the product  $pv$ . For an insulated system not interacting through heat and work with surroundings the balance of energy is constant. Such a system is called an isolated system with surroundings and would require insulation of the surroundings in Fig. 1. Such system is called an isolated system with surroundings and would require insulation of the surroundings in Fig. 1. An isolated system, not being in equilibrium, always strives towards a state of equilibrium. This type of process is called a spontaneous process. The reversal of a spontaneous phenomenon is impossible. This is the most general formulation of the II LT (Principle of the Director), taking into account the existence of a privileged direction of transformation in nature, written mathematically using the entropy function.

Based on the First Law of Thermodynamics, it is always possible to convert work into heat. However, there are limitations

when converting heat into work. If this was not the case, we could build a heat machine that, by taking heat from the environment, would work while simultaneously cooling the environment. We do not observe such phenomena, and a heat machine that would carry out such a process is called a "perpetual motion machine of the first kind". A machine that uses one heat source - is a "perpetual motion machine of the second kind", which is also an unrealistic machine and its operation contradicts, as we shall show, the Second Law of Thermodynamics. A real machine is the one that uses two heat sources. All these machines are schematically illustrated in the  $p-v$  diagram in Fig. 3. According to the I LT, any transformation in which the energy principle is conserved can exist. As reality shows, such transformations cannot always be realized. The above example will suffice. There are very many such examples in life. There are unknown cases of people getting younger, for example, or of heat going spontaneously from a lower temperature to a higher one. In nature, there is a privileged direction in which transformations occur. For their analysis, the simple balance provided by the I LT is not sufficient. Such a balance is insensitive to the direction of occurrence of processes and balances even unreal processes.

Assume that the function we are looking for should increase as the spontaneous transformation in an isolated system approaches equilibrium, and for a reversible process, the attained state should reach a maximum. Such a system is the system together with its surroundings. There are no out-of-environment interactions and such a system is called isolated. The function sought, let us call it the function  $S$ , has the property that:

$$dS_{isol} \geq 0. \tag{10}$$

This function should be a thermodynamic potential, i.e. it should not depend on the type of transformation, but on the state. Such a function was found in 1850 by Clausius and he called it entropy. It is defined as:

$$dS \stackrel{\text{def}}{=} \frac{\delta Q^o}{T}. \tag{11}$$

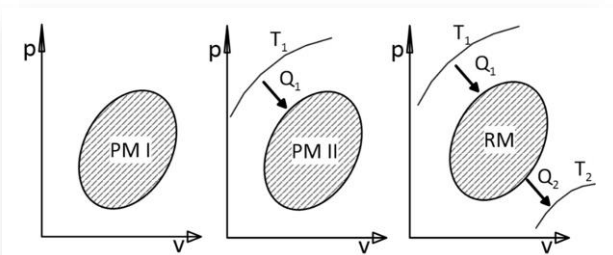


Fig. 3. a) Perpetual motion machine of the first type PMI, without heat source; b) Perpetual motion machine of the second type PMII, one heat source; (c) Real machine RM (two heat sources).

As is well known,  $\delta Q^o$ , the heat transferred by equilibrium transformation, is not a complete differential, whereas  $dS$  is already a complete differential, as can be demonstrated by thermodynamic analysis – the Carnot cycle, or by mathematical analysis – the search for an integrating factor for  $\delta Q^o$  (Carathéodory [8]).

Entropy changes near zero temperature on the Kelvin scale are described by the Third Law of Thermodynamics.

For all isothermal transformations between two equilibrium states, the entropy changes tend towards zero as the temperature of the transformation goes to zero. It is convenient, but not necessary, to assume that the entropies of all components of the system are equal to zero, with the absolute temperature going to zero. This suggestion normalizes the entropies for  $T = 0$ , which was postulated by Planck (1911) [9]. It leads to a simple way of presenting entropy in thermodynamic tables.

Planck's Third Law of Thermodynamics (III LT) [10] ( $s \rightarrow 0$  when  $T \rightarrow 0$ ) leads to the conclusion that the dependent parameters, for example  $x = x(T, s)$  behave as in Fig. 4. The figure shows that when  $\Delta S \rightarrow 0$  and  $T \rightarrow 0$ , the process 1–2 from temperature  $T$  goes to 1'–2' at temperature  $T'$ . As shown earlier, there are relationships between the partial derivatives of the thermodynamic parameters. The III LT obviously affects the values of these derivatives.

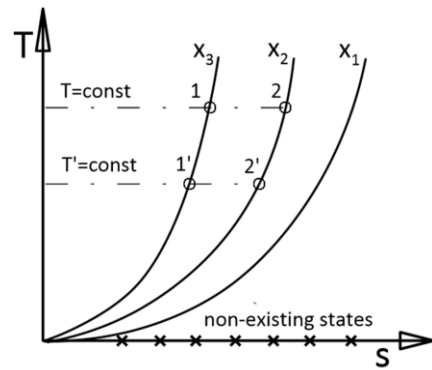


Fig. 4. The dependence of the parameters  $x = x(T, s)$  near absolute zero.

Non-equilibrium processes close to equilibrium states are described by the thermodynamics of non-equilibrium processes, where the Onsager Principle is often regarded as the Fourth Law of Thermodynamics [11,12]. Onsager in 1931 [13] reported that for homogeneously linear independent excitations and homogeneously independent flows, the matrix of phenomenological coefficients is symmetric:

$$L_{ik} = L_{ki}. \tag{12}$$

Onsager's relation about the symmetry of the phenomenological coefficient matrix is a new fundamental assumption of the thermodynamics of irreversible processes and does not follow from previous assumptions of thermodynamics. Generalizations of the Onsager relation were given by Casimir [14]:

$$L_{ik} = \varepsilon_i \varepsilon_k L_{ki}, \tag{13}$$

where:

- $\varepsilon_i = +1$  – for  $\alpha$  type excitations,
- $\varepsilon_i = -1$  – for  $\beta$  type excitations.

Parameters of type:  $\alpha$  that determine the state of the adiabatic system are even functions of particle velocity, e.g. energy and



concentration, while parameters of type:  $\beta$  are odd functions of particle velocity, e.g. momentum density. Ultimately, therefore:

$$\begin{aligned} L_{ik} &= L_{ki}, & \text{when } X_i \text{ and } X_k \text{ are at the} \\ & & \text{same time of } \alpha \text{ or } \beta \text{ type,} \\ L_{ik} &= -L_{ki}, & \text{when } X_i \text{ and } X_k \text{ are of different sign.} \end{aligned} \quad (14)$$

Thermodynamics is not limited only to compressible systems such as fluids, which can do the work of volume change. It also applies to other systems such as simple magnetic substances, electrostatic substances, surface membranes, elastic systems (solids), etc. Systems that perform several types of work are called complex systems. Complex systems are described by more parameters than simple systems, namely at least three. The number of parameters describing complex systems is determined by the Principle of State often referred to in the Anglo-Saxon literature as the Minus First Law of Thermodynamics ( $-I$  LT).

In general, for a complex substance, it can be written:

$$du = \delta q - \sum_1^k X_k a_k, \quad (15)$$

where:  $\delta q$  – unit heat,  $X_k$  – general forces,  $a_k$  – generalized displacement,  $k$  – number of ways in which work is performed.

The state description of the system requires  $(k+1)$  intensive parameters. This follows from the following reasoning:  $k$  ways of performing work require  $k$  "forces" – intensive parameters, in addition, since  $\delta q = T ds$  the intensive parameter is temperature. Thus,  $(k+1)$  intensive parameters are needed to describe one extensive quantity.

### 3. Application of the thermodynamics principles to technology

The principles of thermodynamics allow many technical problems to be solved. Classical thermodynamics does not use a coordinate system, as it deals with equilibrium states in which the intensive parameters (temperature field, pressure field, concentration field) are equalized throughout the volume. Additionally, time does not feature in thermodynamics, due to the fact that it deals with states that have reached equilibrium and is not interested in how long it took for this equilibrium to occur. An important element of thermodynamic analysis is the choice of a system. The classical system is a closed system – associated with a constant and the same number of molecules. For it, the fundamental laws of nature are formulated that energy is constant and entropy changes for irreversible processes are greater than zero. The concept of a closed system is extended in engineering thermodynamics to that of an open system. In an open system, there is a flow of matter causing changes in energy and entropy, Fig. 5.

In thermal power plants, there is a chain of energy conversion: from chemical energy through heat, mechanical energy to electrical energy. The efficiency of a particular process is the ratio of the desired type of energy at the output to the energy at the input. It depends on the physical and chemical laws governing the process.

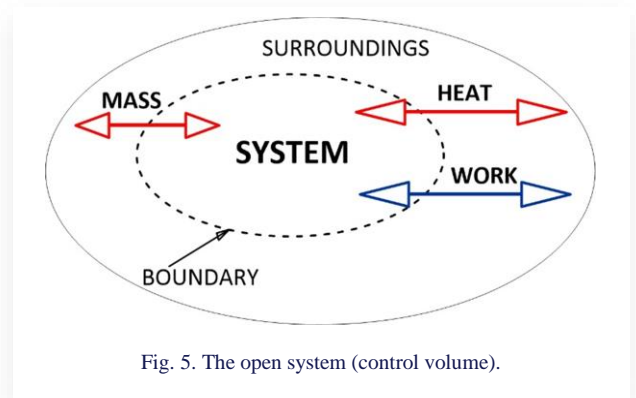


Fig. 5. The open system (control volume).

Since the formulation of the reversible Carnot cycle, many other reversible cycles have been proposed which are modifications of the ideal Carnot cycle that cannot be realized in practice. The Carnot cycle in a  $T$ - $s$  system can be represented by two isothermal processes with constant temperatures  $T_1$  and  $T_2$  and two adiabatic processes with constant entropies  $S_1$  and  $S_2$ , Fig. 6. The heat extracted from source one is:

$$Q_1 = T_1(S_2 - S_1). \quad (16)$$

On the other hand, rejecting heat to the second heat source yields

$$Q_2 = T_2(S_2 - S_1). \quad (17)$$

Work done during the cycle

$$L = Q_1 - Q_2 = (T_1 - T_2)(S_2 - S_1) \quad (18)$$

is equal to the shaded area in Fig. 6. Defining the cycle efficiency as:

$$\eta = \frac{Q_1 - Q_2}{Q_1} = \frac{L}{Q_1}, \quad (19)$$

we obtain

$$\eta_c = \frac{T_1 - T_2}{T_1}. \quad (20)$$

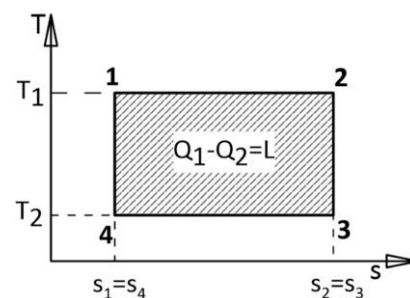


Fig. 6. Carnot cycle in a  $T$ - $s$  diagram.

The Carnot cycle is a reversible cycle and therefore has the highest efficiency in a given temperature range. The efficiency of the Carnot cycle does not depend on the properties of the working fluid, but on the temperatures of the heat sources. It can serve as a thermometer. By defining a reference temperature, for example the triple point of water  $T_2 = 273.16$  K, the temperature

$T_1$  can be measured by measuring the heat, as stems from Eq. (19). In practice, no such measuring instruments are built, hence the temperature defined by the Carnot cycle is called thermodynamic. Any reversible cycle can be thought of as a composition of infinitely many elementary Carnot cycles, as shown in Fig. 7. Such a cycle can be realized with an infinite number of heat sources at different temperatures. Many of these are so-called comparative cycles, i.e. sets of transformations that replicate the actual processes in thermal machines. Determining the efficiency of a device in which energy is converted requires the application of not only the first, but also the second law of thermodynamics, since the conversion of any kind of energy always leads to the conversion of part of it into heat, resulting in a consequent change in the entropy of the system.

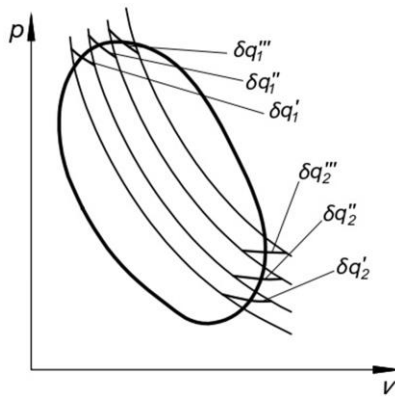


Fig. 7. The cycle decomposed into elementary Carnot cycles.

### The ability to do work is a measure of the quality of energy.

The reference level of this measure is the environment, whose capacity to do the work is zero. A measure of energy quality based on the entropy function has been called exergy assuming  $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$  (steady-state) and  $e = h + e_k + e_p$ :

$$\dot{L} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{m}(e_{in} - e_{out}). \quad (21)$$

The second law of thermodynamics (II LT) related to the environment can be written in the following form:

$$\dot{S} = \frac{dS}{dt} = \frac{\dot{Q}_{out}}{T_{ref}} - \frac{\dot{Q}_{in}}{T} + \dot{m}(s_{out} - s_{in}) \geq 0, \quad (22)$$

or eliminating  $\dot{Q}_{out}$  by means of relation (21) as:

$$\begin{aligned} \dot{S}T_{ref} &= \dot{Q}_{in} \left(1 - \frac{T_{ref}}{T}\right) + \\ &+ \dot{m}[(e_{in} - e_{out}) - T_{ref}(s_{in} - s_{out})] - \dot{L} \geq 0. \end{aligned} \quad (23)$$

Formula (23) gives the expression for the maximum work of the system equal to:

$$\begin{aligned} \dot{L}_{max} &= \dot{Q}_{in} \left(1 - \frac{T_{ref}}{T}\right) + \\ &+ \dot{m}[(e_{in} - e_{out}) - T_{ref}(s_{in} - s_{out})]. \end{aligned} \quad (24)$$

In the case of a closed system ( $\dot{m} = 0$ ),  $\dot{L}_{max}$  yields:

$$\dot{L}_{max} = \dot{Q}_{in} \left(1 - \frac{T_{ref}}{T}\right), \quad (25)$$

which is the same as work obtained in the Carnot cycle, as  $\eta_c = 1 - \frac{T_{ref}}{T}$ . When heat is converted into work in a system, the formula for the efficiency of such a process (defined using I LT) is of the form:

$$\eta^{I LT} = \frac{\dot{L}}{\dot{Q}_{in} + \dot{m}e_{in}}. \quad (26)$$

For the closed system, i.e. when  $\dot{m} = 0$ , the efficiency yields:

$$\eta^{I LT} = \frac{\dot{L}}{\dot{Q}_{in}}, \quad (27)$$

where:

$$\dot{L} = \dot{Q}_{in} - \dot{Q}_{out}. \quad (28)$$

Another definition of efficiency, which takes into account the "quality" of energy, is derived from II LT. This approach also takes into account entropy changes, i.e. the irreversibility of the process, which results in work  $\dot{L}$  instead of work  $\dot{L}_{max}$  being obtained in the cycle. The efficiency calculated in this way is:

$$\eta^{II LT} = \frac{\dot{L}}{\dot{L}_{max}}, \quad (29)$$

where  $\dot{L}$  is given by Eq. (21), whereas  $\dot{L}_{max}$  by Eq. (24). The difference

$$\dot{L}_{max} - \dot{L} = \dot{S}T_{ref} = \dot{I} \quad (30)$$

is the work loss  $\dot{I}$  resulting from the irreversibility of the process. In the case  $\dot{m} = 0$ , Eq. (26) assumes a form:

$$\eta^{I LT} = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in} \left(1 - \frac{T_{ref}}{T}\right)} = \frac{\eta}{\eta_c}, \quad (31)$$

where  $\eta_c$  denotes the Carnot efficiency, that is a maximum attainable value.

Heat engines, the subject of interest in engineering thermodynamics, convert thermal energy resulting from the conversion of the chemical energy of fuels such as coal, oil, gas (combustion) into mechanical work. Fissile materials such as uranium in a nuclear reactor are also used as fuel to produce thermal energy, which in turn is used in thermal machines to produce work (electricity). The efficient use of fossil fuels is necessary and has recently been curtailed due to their limited resources and harmful emissions during combustion. Hence, there has been a recent preference to use 'clean' energy sources, i.e. wind, solar, water and geothermal deposits, as much as possible. These are so-called renewable sources.

A consequence of II LT is that heat goes from a body with a higher temperature to a body with a lower temperature. The greater the difference, the more intensively the heat is transported, but in turn, the efficiency of the conversion of heat energy into work in the case of a thermodynamic cycle decreases. The problem of heat transfer between systems is dealt with by a branch of engineering thermodynamics called heat transfer. Thermodynamics does not analyse the rate of heat energy transfer. That is what heat transfer deals with. In technology, there are processes in which the heat transfer process must be intensified, in order to obtain small heat exchange surfaces, which in turn lead to small dimensions of the heat exchange devices ex-

cuting a thermodynamic cycle. There are also processes that require the reduction or isolation of the heat exchange process, e.g. the insulation of district heating pipelines or the thermal insulation of residential buildings. These two types of processes require knowledge of heat transfer theory. The science of heat transfer is developing on the basis of various industries. One can mention power engineering (heat-to-work conversion problems), chemical engineering, refrigeration, etc. Today, it is difficult to identify processes or phenomena in which heat transfer problems do not occur. The development of the field of heat exchange has been dictated by the development of the leading technologies of civilization. Hence, heat exchange initially developed on the basis of power engineering, and more recently it has developed on the basis of nuclear power and electronics. The cooling of electronic microelements is a challenge for modern heat exchange. Current science and technology is interested in open systems. Apart from technology, open systems are found in biology, medicine, economics, sociology, history, etc. in a closed system, entropy can increase and the system possibly reaches equilibrium. In an open system, the system can reach a steady state with a continuous flow of entropy. An open system is, for example, a living organism, where entropy decreases due to the import of matter along with energy from the environment. The total entropy of living organisms is decreasing, but this does not imply incompatibility with II LT, in light of the above comments.

#### 4. Role of thermodynamics in modern science

Currently, science and technology are interested in the analysis of open systems, which, apart from technology, are found in biology, medicine, economics, sociology, history, etc.

In a closed system, entropy can increase until the system possibly reaches equilibrium. In an open system, on the other hand, the system may reach a steady state with continuous entropy production. A broader definition of energy is “the ability to drive a system transformation”, which clearly includes all kinds of physical and biological processes.

For systems close to equilibrium, entropy strives to reach a minimum of entropy production. Far-from-equilibrium states undergo an evolution to organize a new order. The environment cannot control such transformations. Systems far from equilibrium are strongly non-linear and seek to minimize free energy and maximize entropy. They amplify the amplitude of disturbances and evolve towards new states [15–17].

The II LT for an open system was formulated by Prigogine (1972) [18]. An example of an open system is, for example, a living organism. In living organisms, entropy decreases due to the import of matter together with energy from the environment.

Biological, sociological and economic systems are complex systems and are subject to evolution in a certain direction just like physical systems, they are characterized by the direction of change determined by II LT [19–22]. The complexity of these systems increases with time. Matter flowing through these systems leads to their self-organization and increase in complexity, which confirms that we are dealing with dissipative systems because, in addition to the import of matter and energy, their entropy is generated and dissipated internally.

Statistical entropy is a measure of disorder. Information is a negative entropy and reduces the total entropy in these systems. An irreversible process is the process of changing a microscopic state from a less probable to a more probable state. It does not follow from the statistical formulation of II LT that perpetual motion machines of the second kind do not exist, they are simply unlikely. Systems consume negative entropy or information, but not energy. Generating entropy means consuming negative entropy. This corresponds to the destruction of information or micro-information, which is related to macro-information in communication theory. In science, three different aspects of the entropy concept introduced in the 19th century by Carnot and Clausius can be distinguished:

- the phenomenological aspect with its thermal nature;
- the statistical aspect as a measure of disorder according to Boltzmann, which is a kind of molecular thermal theory of heat; and
- the informational aspect concerning information content according to Shannon, which is part of communication theory.

Many researchers believe that these three formulations are equivalent. This conclusion was first reached by L.M. Brillouin [23] and more recently by J. Peters [24]. This opens up new possibilities for applications of thermodynamics in the areas of medicine, history, social processes, etc.

The first thermal aspect of entropy has already been presented. Let us consider the next ones.

##### 4.1. Statistical entropy

Boltzmann gives entropy as a measure of the disorder of the molecules that make up a system, which can be written as:

$$S = k \sum_i p_i \ln(p_i), \quad (32)$$

where  $k$  is the Boltzmann constant of  $1.38 \times 10^{-23}$  J/K, which is an entropy dimension. The symbol  $p_i$  denotes the probability of a microstate. A microstate of the system is a description of the positions and momenta of all its particles. The large number of particles of the gas provides an infinite number of possible microstates for the sample, but collectively they exhibit a well-defined average of configuration, which is exhibited as the macrostate of the system, to which each individual microstate contribution is negligibly small. For the entropy of the system, the contribution of all degrees of freedom is summed. The total energy of the degrees of freedom is equal to  $E=kT$  and acts as a constraint on the probability  $p_i$ . At low temperatures, some degrees of freedom are frozen and do not contribute to the energy. At zero temperature on the absolute scale, all degrees of freedom have probabilities equal to one or zero and then the entropy value  $S=0$  is obtained, according to the third law of thermodynamics.

The distinction between the microstate of a molecule and the degrees of freedom of a system is important from the point of view of information theory. One can then speak of the entropy of the individual degrees of freedom.

## 4.2. Theory of information

Information, according to Shannon, is the message content of a signal [25]. Each signal occupies a position in the message and can take several discrete values, each with probability  $p_i$ , where  $p_i$  takes values from 1 to  $m$ . The information transported by a given signal  $i$  is equal to  $\log_2 p_i$ . The logarithm at base two is chosen because it gives a unit of information called a bite with 50% probability. The average proportion of information in a message is equal to  $p_i \log_2 p_i$ . A message is the sum of all possible information:

$$S = -\sum_{i=1}^m p_i \log_2(p_i). \quad (33)$$

In binary symbolism  $m = 2$  and  $p = p_1$  or  $p = 1 - p_1$ .

Statistical entropy refers to disorder and information reduces it by introducing order. Let us distinguish between micro-information and macro-information. Microinformation corresponds to the individual degrees of freedom of a system, while macroinformation corresponds to macroscopic signals, each consisting of many molecules and their degrees of freedom. Hence, macroinformation is equal to statistical entropy because it distinguishes the values of each degree of freedom.

The information transmitted is defined as the difference between the sum of all possible signals before and after the information is received. Suppose an item's memory has 1024 responses with equal probability  $p_i = 1/1024$  for each response before the message. Then the information before the message is equal to 10. After the information is received, only one signal is certain and the others have a probability equal to zero. Then, the message received is 10-bit.

## 4.3. Equivalence of information, statistical and thermal entropy

The relations (32) and (33) differ only in sign and in the constant  $k \ln 2$  resulting from the substitution of the logarithm base. As mentioned earlier, statistical entropy is a measure of 'disorder' and information entropy reduces this 'disorder'. The flow of information about the complexity of a system is therefore a flow of negative entropy. The equivalence of thermal and statistical entropy can also be demonstrated based on the perfect gas model.

Consider the irreversible process of expansion of a perfect gas into a vacuum. Because the environment is a vacuum, the system does not work (no back pressure). The system as a whole is insulated, so it does not change energy or temperature.

For an isothermal transformation, there is

$$\Delta L = p\Delta V = \Delta Q, \quad (34)$$

and therefore the entropy change is

$$\Delta S = \frac{\Delta Q}{T} = \frac{p\Delta V}{T}. \quad (35)$$

Using the equation of state for a perfect gas, one obtains:

$$\Delta S = R \frac{\Delta V}{V}. \quad (36)$$

Let us consider the same transformation from the microscopic side. The probability of finding a molecule in the original volume equal to  $V_1$  is:

$$p = \frac{V_1}{V_2}, \quad (37)$$

where:  $V_2$  is the final volume of the transformation. The probability of finding  $N$  particles in the original volume  $V_1$  is even smaller and, due to the independence of events, is:

$$p_N = \left(\frac{V_1}{V_2}\right)^N. \quad (38)$$

Let us logarithmize this relationship:

$$\ln p_N = N \ln \frac{V_1}{V_2}. \quad (39)$$

Assume that  $V_2$  is a little different from  $V_1$ , i.e. that  $V_2 = V_1 + \Delta V$ , then:

$$\frac{V_1}{V_2} = 1 - \frac{\Delta V}{V_2}. \quad (40)$$

When the logarithm is expanded into a series, the result is:

$$\ln \frac{V_1}{V_2} = \ln \left(1 - \frac{\Delta V}{V}\right) \approx -\frac{\Delta V}{V}, \quad (41)$$

and then

$$\ln p_N = -N \frac{\Delta V}{V}. \quad (42)$$

Comparing with the entropy change relationship (35), one obtains:

$$\Delta S = -\frac{R}{N} \ln p_N. \quad (43)$$

Thus, there is a relationship between thermal entropy and the probability of a particular state of the molecules occurring. An irreversible process is a transition from a less probable microscopic state to a more probable one. It does not follow from the statistical formulation of II LT that a perpetual motion machine of the second kind is impossible. It is only very unlikely. It is unlikely that the gas will concentrate back into the original volume, and it is even less likely that the process will repeat itself cyclically.

Classical physics and chemistry consider closed systems. Current science and technology is interested in open systems. As mentioned earlier, such open systems outside of technology are found in biology, medicine, economics, sociology, history, etc. In a closed system, entropy can increase and the system possibly reaches equilibrium. In an open system, the system may reach a steady state with a continuous flow of energy. The change in entropy, in an open system, is expressed by the relation:

$$\Delta S = \Delta S_i + \Delta S_e. \quad (44)$$

In Eq. (44),  $\Delta S_e$  is the change in entropy due to the import of energy in the form of a matter from the environment, and  $\Delta S_i$  – the increase in entropy due to the irreversibility of the transformations taking place in the system.  $\Delta S_i$  is always posi-



tive, while  $\Delta S_e$  can be both positive or negative. Hence, it follows that the entropy of a system can decrease. In living organisms, entropy decreases due to the import of matter along with energy from the environment in the form of food. Although in living organisms the total entropy is decreasing, this does not mean, in the light of the above remarks, that this is incompatible with II LT.

The classical idea of thermodynamics (Second Law of Thermodynamics) assumes an increasing disorder in an isolated system and is in opposition to evolution (self-organization). This applies to closed systems. Biological systems are open systems. They are capable of building complex structures while being fed with "negative entropy" – information. Energy from one form is transformed into another form. Plants transform light into chemical energy. In the muscles of animals and humans, chemical energy is converted into mechanical energy. None of these conversions takes place without loss. Some energy is lost as heat. All biological and chemical processes are accompanied by a dispersion of energy in the form of heat. Heat is associated with a decrease in 'order' in the system. The measure of 'order' in a system is entropy. Higher entropy means greater 'disorder' in the system. As already mentioned in an isolated or isolated system, an increase in entropy is assumed to yield the Second Principle of Thermodynamics.

Irreversible processes that exist in any mechanical system, biological system, economic system, etc. depend on the nature of the sources and sinks of energy. These cause an increase in entropy in the system. For an open system, there is also the exchange of entropy with the environment. Any flow of energy from a source at temperature  $T_1$  to a sink at temperature  $T_2$  is constrained by the Carnot relation for irreversible processes:

$$\frac{Q_2}{T_2} - \frac{Q_1}{T_1} \geq 0, \quad (45)$$

where  $Q_1$  is the heat entering the system and  $Q_2$  is the heat leaving the system. The heat flow through the system must be caused by a temperature gradient. Inserting (45) into (44) we get:

$$\Delta S = \Delta S_i + \frac{Q_1}{T_1} - \frac{Q_2}{T_2}. \quad (46)$$

According to Eq. (45), the difference in heats in (46) is negative.

Relationship (45) satisfies the necessary condition for the self-organization of a system associated with evolution, as it shows that a system can reduce its entropy through energy flow. If the system does work (living organisms – fauna) then:

$$L = Q_1 - Q_2, \quad (47)$$

and the resultant change in entropy yields:

$$\Delta S = \Delta S_i + \frac{Q_1}{T_1} - \frac{Q_2}{T_2} + \frac{L}{T_2} = \Delta S_i + \frac{L}{T_2} - Q_1 \frac{T_1 - T_2}{T_1 T_2}. \quad (48)$$

The last term in Eq. (48) is negative which causes the entropy to decrease by energy flow. The same is true if the system only builds up its chemical potential through energy flow (flora). In that case:

$$\Delta H = Q_1 - Q_2, \quad (49)$$

$$\Delta S = \Delta S_i + \frac{\Delta H}{T_2} - Q_1 \frac{T_1 - T_2}{T_1 T_2}. \quad (50)$$

The useful energy potential for biological systems is the Gibbs free energy potential:

$$\Delta G = \Delta H - T\Delta S \quad (49)$$

or

$$\Delta H = \Delta G + T\Delta S. \quad (50)$$

The flow of energy and the associated flow of information through open systems such as biological systems is the thermodynamic explanation for the generation of their complexity and evolution. Evolution in biology is characterised by a concentration of thermodynamic potential and a race between energy dispersion and information flow.

Classical thermodynamics operates with systems at or near equilibrium. A new category of complex systems is in non-equilibrium states. Classical systems tend towards equilibrium, i.e. towards disordered states of matter, while complex systems evolve towards order. For systems close to equilibrium, entropy production tends towards a minimum. States far from equilibrium undergo evolution by organizing a new order. The environment is unable to control such transformations. Systems far from equilibrium are strongly non-linear and tend towards a free energy minimization and entropy maximum. They amplify the amplitude of disturbances and evolve towards new states.

Biological, sociological economic systems are complex and evolve in a specific direction. It can be thought that, as in physical systems, there is a time arrow in them defined by the Second Principle of Thermodynamics. Over time, the complexity of these systems increases. Matter passing through these systems leads to 'self-organization' and an increase in the complexity of the system. Often such systems are called 'dissipative' because, in addition to the import of matter and energy, entropy is generated and dissipated within the system. Static entropy is disorder, while information is negative entropy or negative entropy.

Consumed by a complex system is not energy, but rather negative entropy or information. The generation of entropy means the consumption of negative entropy. This corresponds to the destruction of information.

Information plays an important role not only in physics and technology, but also in biology and economics, e.g. the cost of making a detail depends on its complexity. The arrival of a new technology for making a workpiece changes the cost relationship of making a workpiece. The result of human work is the flow of information. Good workmanship needs more information, etc.

Information and thermodynamics are important in the interaction and self-regulation of complex systems.

Living organisms as well as other complex systems are driven by information and organized by dissipative processes. The basis for the instability of dissipative systems is the non-linear interaction between the micro-elements of a system that is far from equilibrium. This interaction leads to the organization of the macroscopic state and various bifurcations of the states of the system. The system then moves away from thermodynamic equilibrium to more likely structures at the point of bifurcation. Dissipative systems evolve using feedback in the form of an information loop.

Biological information includes genetic DNA codes. Biological systems are dissipative and self-organizing systems and re-

duce entropy. Life is a process of entropy reduction. The thermodynamics of open systems applies to it. By studying populations of living organisms, one can conclude that they are dissipative structures.

In dissipative biological structures, the memory of the past is a conservative element and danger and threat cause the organisms to move away from a state of equilibrium and self-organization. This is the learning capacity of organisms.

Classical cybernetics uses analyses based on the Shannon information. Some developments in artificial intelligence are related to the thermodynamics of open systems. It should be noted that many artificial intelligence concepts are based on the Shannonian approach. The development of artificial intelligence has enriched psychology and neurophysics.

The development of culture is manifested in the development of language, music, literature, technological knowledge and science. The theory of these fields is based on the theory of complex entropic systems.

More recently, socio-economic and cultural aspects have been analyzed using entropy and self-organizing dissipative structures. Thermodynamics is a new tool for analyzing socio-economic processes. Economics is determined by the development of technology. Technological innovation is an important element in the evolution of economics.

The development of history is controlled by an entropic process. History is a series of bifurcations in a social system far from equilibrium states. The course of history is determined by socio-economic and cultural changes. When there is no innovation and there is socio-cultural stability then there is stagnation and no change. Changes in the socio-technological set-up can lead to revolutionary change through positive feedback. From the point of view of dissipative structures, catastrophe (revolution) arises from internal perturbations reinforced by the environment. The catastrophe leads to a point of bifurcation and to a new level of stability. The new state of the community is more complex after this transition.

## 5. Conclusions

As has been attempted to show, the thermodynamic principles given are general and can apply to different physical objects. The method of analysis is the same. First, the state of the system is determined, so the thermal and caloric equations are given, then the energy balance (ILT) is used and the reality of the transformation and direction is investigated using II LT. Usually, for the determination of the parameters, systems will behave in a particular way that can be described by simple analytical relations. This behaviour of a substance is considered in thermodynamics as a model. Thus, a real gas is modelled as a perfect gas, a model of a simple magnetic substance is a substance described by the Curie equation of state, a model of an elastic substance is a substance described by Hook's law, and so on.

Classical thermodynamics serves as the analytical tool for determining work, energy, or thermodynamic effects related to heat and temperature, focusing solely on equilibrium states without predicting process rates due to the absence of explicit time representation, although II LT inherently relates to the time axis. In highly dilute systems where statistical laws are inapplicable, phenomenological thermodynamics based on the observation of highly probable phenomena also does not apply, as

II LT fundamentally relies on the probability of phenomena occurring, particularly for microscopic phenomena, on a high probability basis.

The thermodynamics of irreversible processes employs the second law of thermodynamics, defining stationary states similar to equilibrium states delineated by II LT in classical thermodynamics. Linear thermodynamics of non-equilibrium processes near equilibrium states has been developed, with non-linear thermodynamics introduced for stationary states far from equilibrium. The thermodynamics of non-equilibrium processes addresses problems involving irreversibility caused by multiple 'thermodynamic forces', each leading to specific branches of thermodynamics, such as heat exchange, mass exchange, and momentum exchange, governed by differential equations and their boundary conditions.

The Laws of Thermodynamics attempt to describe and quantify complexity growth, information storage, distance from thermodynamic equilibrium across different hierarchical levels, and ecosystem development strategies. Equilibrium thermodynamics is more easily described mathematically compared to non-equilibrium thermodynamics due to the non-deterministic nature of self-organizing complex systems. Simplifying models for formal statements of self-organization may limit applicability to real systems and overlook their complexity, although tentative fourth laws aim to establish clear links between thermodynamics, ecology, and evolution.

Thermodynamics has evolved into a comprehensive knowledge system encompassing almost all life sciences branches [26]. Virtually every aspect of reality can be described in thermodynamic terms, reflecting its universal applicability. Despite the complexity within living systems, thermodynamics can be defined as the general science of energy, not only explaining energy transformations in human-dominated devices but also encompassing energy and matter transformations across all systems in the biosphere and beyond.

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