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THE CONCEPT OF ENTROPY IN PHYSICS

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Abstract. Entropy is one of the most important concepts in physics, but also one of the most abstract and difficult to understand physical quantities. Historically, this concept arose in thermodynamics, studying the conversion of heat into work and the transfer of heat from a body with a high temperature to a body with a low temperature. Subsequently, this concept acquired other interpretations in contexts such as statistical mechanics and information theory.
This article is devoted to revealing the essence and content of the concept of entropy, which played a major role in the development of physics and thermodynamics.

Key words:entropy, information , heat engines, thermodynamic probability, state function, Carnot cycle, amount of heat.

Аннотация. Энтропия является одним из важных понятий в физике, но также и одним из самых абстрактных и трудных для понимания физической величиной. Исторически это понятие возникло в термодинамике при изучении преобразования теплоты в работу и перехода тепла от тела с высокой температурой к телу с низкой температурой. В дальнейшим у этого понятия появились другие толкования в контекстах, например статистической механики и теории информации. Данная статья посвящена к раскрытию суть и содержания понятии энтропию, которой играл большую роль в развитии физики и термодинамики.

Ключевые слова: энтропия, информация, тепловые машины, термодинамическая вероятность, функция состояния, цикл Карно, количество теплоты.

Introduction. One of the most important thermodynamic quantities, playing a major role in the calculations of various thermodynamic processes, is entropy. Subsequently, entropy, introduced into thermodynamics, attracted the close attention of not only physicists, but also all scientists and thinkers (philosophers, writers, etc.) due to the philosophical aspect of the second law of thermodynamics, written in terms of this physical quantity. [1].

The concept of entropy is important not only for physics, but also for statistical mechanics, information theory, etc. For example, Claude Shannon, an American engineer, mathematician, and the "father of information theory," proposed using entropy as a measure of unpredictability. (uncertainty) of data. Numerically, it is equal to the amount of information per message symbol, and the unit of measurement of information is the bit.

A message is, for example, a sentence in Russian. Different letters in it convey different amounts of information: frequently occurring letters convey less, while rare letters convey more. This is clearly demonstrated by Morse code. For example, a longer string is used to encode the letter Ш than, say, the letter Е. This means that Ш is not as simple and obvious as Е—it has more entropy. Sequences of symbols also have more or less unpredictability. For example, in

Russian, it is very unlikely that two consecutive Es will be followed by a third. Consequently, the conditional entropy of the letter E is quite low. [3].

Messages form entire layers of information—masses of text. And the greater their uncertainty, the greater their value. A business letter has very little unpredictability, but also little interest for the reader. In a good work of fiction, it's precisely the opposite. The entropy of a newly published piece of news is very high, but after it's reprinted by other media, it drops, but so does interest. The higher the entropy of a message, the greater its "information value," according to Shannon. So entropy, chaos, and change aren't as bad as they seem? [3].

Most of the physical quantities that engineering students in technical universities encounter when studying physics are already familiar to them from the school physics course: energy, amount of heat, force, moment of force, etc. For physical quantities that are not mentioned in the school course, there is one thermodynamic quantity that is exceptionally important for understanding the physical picture of the world, which is not mentioned in the school physics course and for which there are no analogues, this is entropy [5].

In the scientific literature there are publications in which the place of entropy is incorrectly used as potential energy, which depends on temperature [5].

The main goal of this article is to clarify the essence and content of the concept of entropy.

The concept of entropy was introduced into thermodynamics by R. Clausius in 1865 to denote a physical quantity that was interpreted as a quantitative measure characterizing the transformation of heat into work. This name was derived from the Greek word "trop," a transformation reminiscent of the closely related word "energy." This concept was introduced by Clausius based on his study of heat engines, following the work of Carnot. Based on the postulate that "heat cannot spontaneously pass from a cold body to a hot one," he formulated the second law of thermodynamics. Clausius demonstrated that there is a state function that relates the quantity of heat and absolute temperature in a reversible cyclic process. It is this function that he called entropy. The defining equation for entropy in this approach is the well-known equation

$$dS=\frac{\delta Q}{T}(1)$$

where δS - the change in the entropy of a system at an absolute temperature T during a reversible heating process, for which δQ is the elementary amount of heat added to the system. The energy introduced in this way for reversible processes is a function of the state of the thermodynamic system. [2].

Systems and is applicable to any process, reversible or not. However, the procedure proposed by Clausius is abstract and not very clear to students, and equation (1) has no obvious physical meaning. The meaning of entropy is revealed in static physics. Entropy is associated with the thermodynamic probability of a system's state. Boltzmann gave the concept of entropy a deeper statistical meaning. He introduced the concept of thermodynamic probability W of a system's state—this is the number of microstates in the system that realize a given macrostate. Thermodynamic probability differs from its mathematical definition; it is greater than one. According to Boltzmann, thermodynamic probability and entropy are related by the relation:

$$S=k\ln W(2)$$

Therefore, entropy is considered a measure of the probability of a system's state. Boltzmann's formula provides a statistical interpretation of a system's entropy as a measure of its disorder. The greater the number of microstates, the more disordered the system. Equilibrium is the most probable state, and the number of microstates in the system is maximum. If a closed system consists of several bodies, the entropy of the system is equal to the sum of their entropies, i.e., entropy is additive.

Real processes are irreversible. Therefore, it can be argued that real processes lead to an increase in entropy. However, all of the above applies to systems consisting of a large number of particles. This assertion may be violated in systems with a small number of particles due to fluctuations in the probability of states .

Furthermore, Shannon's adoption of von Neumann's suggestion to use the word entropy, given the similarity of his information equation to formula (2), represents an additional source of confusion that is added to the idea of disorder. Identification entropy with disorder, although it is mentioned by Boltzmann in his description of molecularly ordered or disordered configurations, rather hindered than contributed to the understanding of entropy, as claimed in various physical and historical studies [1].

In a book by German popularizer Professor Felix Auerbach entitled "The Queen of the World and Her Shadow," energy and entropy—two fundamental concepts of thermodynamics—are described with pomp and romance. The author's brilliant talent enabled him to make one of the most difficult philosophical problems in physics accessible to a wide readership [6,7].

“Energy reigns over everything that happens in boundless space, in the flow of fleeting time, like a queen or a goddess, illuminating with its light both a blade of grass in a field and a man of genius, here giving, there taking away, but on the whole remaining quantitatively unchanged... But where there is light, there is also a shadow, whose name is Entropy. Looking at it, one cannot suppress a vague fear within oneself - it, like an evil demon, tries to belittle or completely destroy all the beauty that the bright demon - Energy - creates. We are all under the protection of Energy, and all are sacrificed to the hidden poison of Entropy... The amount of energy is constant, but the amount of entropy grows, devaluing energy qualitatively. The sun shines, but the shadows grow longer. Everywhere there is dispersion, leveling, devaluation...” [7].

In G.N. Alekseev's book "Energy and Entropy," the front cover contains the most interesting statement about energy and entropy: "Energy and Entropy. The Queen of the World and Her Shadow." Everything on Earth arises and develops thanks to energy, everything is destroyed and dies with the growth of entropy. Energy is the source and measure of the movement of matter and the action of forces, while entropy is the measure of their gradual extinction. People understood this only a little over a hundred years ago... [8].

It's worth remembering that the question of the best practical use of heat engines arose in the first quarter of the 19th century. Sadi Carnot succeeded in establishing the conditions for the most advantageous use of heat engines. He demonstrated that the efficiency of an ideal heat engine depends on the temperature of the heater and coolant:

$$\eta = \frac{T_1 - T_2}{T_1} \quad \text{or } \eta = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} \quad (1)$$

where Q_1 is the amount of heat received from the heater, Q_2 is the amount of unused heat transferred to the cooler. Carnot described the closed cycle of an ideal engine. The Carnot cycle consists of isothermal expansion of the gas (1-2), adiabatic expansion (2-3), isothermal compression (3-4), and adiabatic compression (4-1) (see Fig. 1).

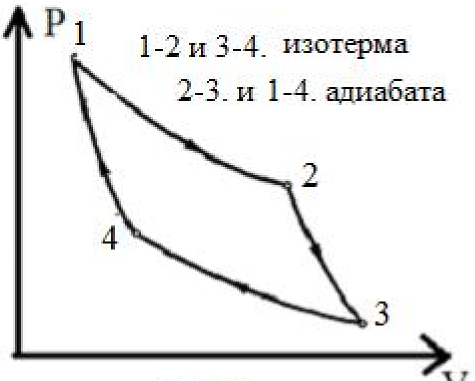

Рис.1

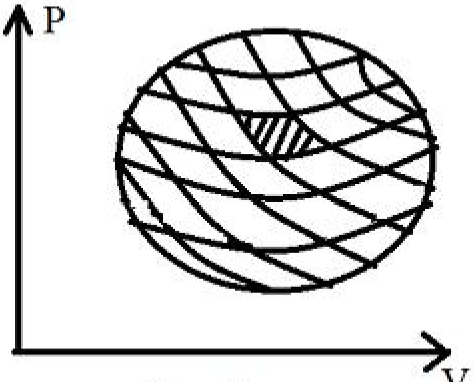

Рис.2

With this combination of isothermal and adiabatic processes, the following relationship can be obtained:

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1} \quad \text{or} \quad \frac{Q_1}{T_1} - \frac{Q_2}{T_2} = 0 \qquad (2)$$

These ratios can also be obtained from expression (1).

After completing an ideal Carnot cycle, the working fluid (gas) returns to its original state, completely identical to the initial one, and the cycle can be repeated an unlimited number of times. The area bounded by the cycle graph expresses the useful work of the heat engine (Fig. 1). From expression (2), the fraction $\frac{Q}{T}$ clearly characterizes the state of the working fluid, and the previous equality mathematically confirms that the cycle does not result in any disturbances to the working fluid's state. Furthermore, reversing the sign will not violate the equality. Consequently, this cycle can also proceed in the opposite direction [6].

The cycle corresponding to any ideal circular process can be represented as a sum of infinitesimal Carnot cycles (Fig. 2). Using integral calculus, we can write in this case:

$$\oint \frac{dQ}{T} = 0 \qquad (3)$$

Where dQ is the infinitesimal amount of heat for each elementary Carnot cycle. R. Clausius demonstrated that the above integral expression allows us to determine a certain function—the state of the system or the difference between the final and initial states. He coined the term "entropy" for this function. Thus, for a reversible process in which no change in state has occurred, the difference in entropy between the final and initial states is zero. This is written as follows:

$$S_k - S_н = \frac{dQ}{T} = 0 \qquad (4)$$

However, a reversible process is a pure idealization. There are no reversible processes in nature. Nothing passes without a trace. No process can reverse itself and return a system to its initial state without leaving behind consequences.

Real processes are irreversible. A gas can expand if given enough space, but no one has ever observed a gas spontaneously contracting. Such examples abound, as discussed above. The change in entropy for an irreversible (real) process should be written as follows: $S_н - S_к < 0$ i.e., the entropy at the end of the process is greater than at the beginning. In real irreversible processes, entropy always increases.

Clausius formulated the fundamental laws of thermodynamics as the fundamental laws of the universe in the following simple form :

1. The energy of the world is constant.
2. The entropy of the world tends to its maximum.

The irreversibility of real processes is associated with the inevitable devaluation of energy when part of it is converted into the internal energy of surrounding bodies.

The nature and content of entropy are multifaceted; it is used in all fields of science and technology. In statistical physics , entropy characterizes the probability of a given macroscopic state occurring . In addition to physics and thermodynamics, the concept of entropy is widely used in mathematics: information theory, mathematical statistics , and so on. In these fields, entropy is defined statistically and is called statistical or informational entropy. Furthermore, entropy is used in chemistry (for calculating the equilibria of chemical reactions, binding energy, etc.), synergetics, and other fields of science.

In this paper, we have covered the thermodynamic and statistical meanings of entropy. Thermodynamic entropy is widely used to calculate thermal processes (analyzing the operation of heat engines and refrigeration units) and other thermal engineering devices.

Conclusion

Based on the literature review conducted to reveal the essence and content of the concept of entropy, the following conclusions can be drawn:

1. The concept of entropy and its historical origin was analyzed.

2. The essence and content of the concept of entropy, which is used in all areas of science and technology, is considered.

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