

Issues of Teaching Non-Equilibrium Thermodynamics Elements in Higher Technical Educational Institutions

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ABSTRACT

In the article, out-of-balance situations arising due to the exchange of energy and matter with the external environment in open systems are described. A comparative analysis of the thermodynamics of linear and nonlinear non-equilibrium states of irreversible processes is presented. As a result of the decrease of entropy in open systems with a strong unbalanced state, the formation of self-ordered spatial and temporal dissipative structures from states of disorder or chaos in the system has been shown.

Introduction:

The world around us consists of systems that are in a state of considerable imbalance. Many non-equilibrium states can also be observed in the solar system. For example, the Solar wind, consisting of a strong flow of charged particles, can cause various disturbances and cyclones as a result of significant impact on the magnetosphere and atmosphere of the planets. The alignment of the planets and the Sun creates unstable conditions in the Sun's atmosphere. In general, it is necessary to consider the Sun and the planets and the space between them as a whole significantly unbalanced and non-linear system. In addition, in recent years, research has been carried out on the acquisition, study, and practical application of substances in non-equilibrium states. The properties of substances in extreme conditions, i.e. in strong non-equilibrium conditions, are being studied. For example, very low and high temperatures, very

high pressure, high-energy particles, strong flow of high-intensity laser beams, strong electric and magnetic fields, and other factors are being studied. As a result of such research, new technologies for changing substance properties and obtaining substances with desired properties are emerging. Therefore, the teaching of elements of non-equilibrium thermodynamics is an urgent issue in higher physics education. However, it should be noted that the issues of thermodynamics of non-equilibrium systems in higher education institutions where physics is taught are not sufficiently covered in the curriculum and not sufficiently covered in the educational literature. This article is devoted to the clarification and teaching of non-equilibrium thermodynamics issues in higher physics education.

MAIN PART

Non-equilibrium thermodynamics is a theory that studies irreversible non-equilibrium processes occurring in open systems. Non-equilibrium thermodynamics studies the rate of these processes as a function of external conditions. Systems that exchange energy, matter, or information with the external environment are called open systems. Dissipation occurs in complex open systems. Dissipation refers to the extinction of various actions in the system, the transformation of energy into heat, etc. One example of non-equilibrium processes is migration events. In these phenomena, the temperature gradient causes heat flow, and the concentration gradient causes mass flow. It is called thermodynamic forces that generalize the gradients of the considered quantities. The emergence of currents under the influence of thermodynamic forces violates the state of statistical equilibrium. But in balanced systems, internal relaxation processes occur that bring them back to equilibrium. It is known from experience that for most irreversible processes, currents are linear functions of thermodynamic forces. For example, Fourier's law establishes linear relationships between heat flow and temperature gradient, and Fick's law establishes linear relationships between mass flow and concentration gradient. Therefore, it is necessary to distinguish between linear thermodynamics of irreversible processes and nonlinear non-equilibrium thermodynamics based on linear relations of flow and thermodynamic forces. The system is in a non-equilibrium stationary state if the external influence that keeps the system in the non-equilibrium state does not change. Entropy is constantly changing in a non-equilibrium system. If the flow (I_i) and thermodynamic forces (X_i) are non-zero, the rate of

increase of entropy (change of entropy) $\sigma = \frac{dS}{dt} = \sum_{i=1}^n I_i X_i$ can be expressed in the form For the

total entropy not to change, it is necessary to continuously transmit a current from the given system to the external environment or to receive an external current from the external environment to this system. If the entropy of the system has a maximum value in an equilibrium stationary state, the rate of entropy growth (generation) in a non-equilibrium stationary state has a minimum value according to Prigogine's theorem. If the system is in a state of disequilibrium due to some unchanging external influence and cannot return to the state of equilibrium, the system tends to a state where the rate of increase of entropy is minimal. Prigogine's theorem is valid for situations where the system is not far from equilibrium. A non-equilibrium quasi-stationary state in which the entropy growth rate is minimal is stable. In any stationary state, fluctuations occur in the values of system parameters. If the resulting fluctuation decays with time, the state is stable. Internal processes occurring spontaneously in the system in the steady state dampen the fluctuations. Arbitrary stationary states are necessarily stable in linear

thermodynamics. During the evolution of the system, as a result of the decrease in the entropy growth rate, the tendency to a stationary state in the linear field is monotonous, and the system cannot "jump" from this state. Therefore, in the linear domain not far from equilibrium, no oscillations occur around the stationary states. When there is interaction between two systems, there is a flow of entropy from one system to the other. When a non-equilibrium state occurs in an isolated closed system, the processes continue until the entropy reaches its maximum value. In open systems, however, entropy outflows can balance entropy gains within the system. Under such conditions, stationary states appear and are maintained in the system. As a result of the occurrence of non-equilibrium processes in a state sufficiently far from equilibrium, an instability very sensitive to fluctuations in the state of the system appears, and the fluctuations become larger, and the system leaves this stationary state by itself. For example, in a non-equilibrium stationary state, a fluctuation of one of the generalized thermodynamic forces can lead to an increase in the rate of entropy growth, and as a result, the system leaves the stationary state.

In open systems, it is possible to control the course of processes by changing the flow of energy and matter from the outside and directing the evolution of the system toward states far from equilibrium. If the state of the system is far from the equilibrium state, the linear relationship between currents and thermodynamic forces is broken. Under certain non-equilibrium conditions, the entropy decrease of the system due to the exchange of currents with the external environment creates instability in the system state, and large-scale fluctuations occur and increase to the macroscopic level. As a result of this, the formation of self-ordered spatial and temporal dissipative structures is observed in the system from states of disorder or chaos. As a result of the evolution of the system, these structures may be replaced by other new structures with a higher level of complexity and order. An example of a spatial structure is Benard cells that form in liquids. If the liquid layer is strongly heated, a temperature gradient is formed between the upper and lower layers. At small values of the temperature gradient, heat is transferred from the lower layer to the upper layer by heat conduction. When the temperature gradient exceeds a certain critical value, a convective flow with a characteristic structure in the form of hexagonal cells appears. Inside the cell, the relatively hot fluid rises to the top, and the relatively cold fluid moves down along the edges of the cell. Convection cells are highly organized structures that result from the collective, organized movement of molecules. A similar giant structure of cells exists in the sun. This structure forms a convective zone consisting of a spherical layer with a thickness of 10^5 km.

The enormous thermal energy released as a result of the thermonuclear reaction taking place in the Sun's core is transferred to the Sun's surface and atmosphere through this convective zone. Laser radiation is an example of a dissipative space-time structure. At small values of the "damp" power supplied to the laser working material from outside, the number of excited atoms is relatively small, and each atom starts to emit light independently. In this case, the device works in normal lamp mode. Starting from a certain critical value of the external "instillation" power, the number of awakened atoms increases dramatically, interrelationships, and correlations are established between them, and a state of high-level organization is created. All excited atoms together produce laser radiation with high coherence and high intensity in the same phase. Self-organization is a common feature of open systems. In the analysis of self-organization processes, the concepts of linear thermodynamics of irreversible processes cannot be used, since the formation of these structures occurs in situations far from equilibrium. The

formation of structures in open systems has a limited character. In conditions greater than a certain critical value of the external influence, the fluctuations increase to the macroscopic level, and a new structure or regime is established. Therefore, the jump change in the state of open systems at the critical point is also called a non-equilibrium phase transition. External influences that cause phase transitions require that micro processes occur in an organized state in the system. For example, convective motion in Benar cells or coherent laser radiation requires a high level of organization from a molecular perspective.

The concept of entropy and the second law of thermodynamics can also be applied to living nature. If we consider the world we live in as a closed system, during the evolution of the system, according to the second law of thermodynamics, the entropy of the system increases and reaches its maximum value, and disordered states are resolved. Life on Earth consists of a huge fluctuation that occurred temporarily during the evolution of the system, and eventually, all the ordered structures should collapse and go to a disordered state, and the "heat death" of the system should be decided. However, based on the concepts of non-equilibrium thermodynamics, the biosphere consists of an open system in which matter and energy are exchanged with the external environment, and in this system, it is natural that there is a local decrease in entropy and the existence of living life in the form of an ordered dissipative structure. The biosphere and life on Earth are a kind of "ordered structure" and exist due to the reserve of negentropy on Earth. The biosphere receives energy from the high-temperature ($T=600\text{K}$) Sun, recycles it, and returns it to the universe at a low temperature ($T=300\text{K}$). In this case, the entropy of the biosphere, which consists of an open system, decreases, ie: $\Delta S = \frac{Q}{T_1} - \frac{Q}{T_2} < 0$. Therefore, life on Earth exists due to negentropy coming from the Sun.

CONCLUSION

In open systems where dissipative structures are formed, the second law of thermodynamics is not violated. In smaller dissipative open systems where structures are formed, the entropy of this system decreases due to outward flow. If we treat these smaller open systems as components of a larger isolated system, the total entropy of the larger system increases and there is no conflict with the second law of thermodynamics.

The combination of the second law of thermodynamics with the property of self-organization has become one of the greatest achievements of modern thermodynamics. As a result of providing students with knowledge on modern non-equilibrium thermodynamic issues in higher education institutions where physics is taught, new ideas about the scientific landscape of the universe are formed in them.

Continually familiarizing students with the achievements of modern physics, and establishing the teaching of new fields of physics that have been formed, helps to increase the efficiency and quality of education. It ensures that the knowledge, skills, and abilities of future professionals are more advanced, perfect, and up to date.

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