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ON THE CENTENNIAL OF A. V. LUIKOV

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SCIENTIFIC HERITAGE

Time is indomitable, inexorable, merciless. And only in the memory of associates and friends does A. V. Luikov remain as vivacious, congenial, and inimitable as he was in life where he joked, loved, dreamed, created, lived. A scholar and a whole-hearted toiler in science, he was an active participant of everything remarkable that was linked with his time, his epoch. A son of his time and its active creator, he made a momentous contribution to science and left an indelible vestige in time. Much is being slowly buried in oblivion, remaining only a fact from the past, much has merely sunk into the Lethe. Such are the laws of life. Distinguished by rigor and beauty of mathematical calculations, ingenuity of ideas, and originality of representation, the scientific works of A. V. Luikov are now as timely as when they were created. A. V. Luikov was a man of great erudition, had a subtle sense of humor, and was highly cultured spiritually. By nature he was very delicate and sympathetic, ready to lend a helping hand at any second, and generously shared knowledge and ideas with his pupils. He won great recognition and genuine respect of the international society of scientists-thermal physicists.

Aleksei Vasilievich Luikov was born in 1910 in the town of Kostroma. After graduating from the physico-mathematical department of the Yaroslavl Pedagogical Institute in 1930 he was a teacher at the workers' faculty of power engineering in Yaroslavl and then a scientific worker in the Drying Laboratory of the All-Union Heat Engineering Institute. Here he carried out his first research on drying kinetics and the development of methods for determining thermal physical characteristics of moist materials. In 1931 he was granted the first inventor's certificate "Variable-Pressure Drier" for his work on dehydration of moist porous materials at a variable vapor pressure.

As early as 1932 A. V. Luikov conducted experiments to investigate moisture-content fields in convective drying of capillary-porous bodies (filter paper disks) for analyzing drying kinetics and dynamics. As a result, he detected inflections of the curves of the moisture-content distribution across the body thickness that corresponds to the location of the evaporation surface. At the same time, from analyzing the moisture-content fields it was found that there is no clearly defined boundary between the evaporation surface and the immediate layers as is the case with the frost line of ground in the Stefan problem. Thus, evaporation proceeds not only on the deepened surface but also across the entire body thickness. However, most of the evaporating liquid goes off from the evaporation surface.

Based on the conducted experiments A. V. Luikov for the first time suggested temperature curves for analyzing drying kinetics, including those for studying the mechanism of deepening of the evaporation surface.

In 1932 Aleksei Vasilievich enrolled in the courses of postgraduate training at the Scientific Research Institute of Physics of Moscow University, where prominent scientists such as A. P. Mlodzeevskiy, I. V. Luzin, A. S. Predvoditelev, I. E. Tamm, et al. worked; these scientists had a large influence on shaping his creative capabilities and scientific activity.

In 1932–1935 A. V. Luikov focused on the problem of transfer in colloidal and capillary-porous bodies. He developed a novel method of determining thermal physical characteristics of moist materials. In 1935 he established a new phenomenon, namely, thermal diffusion of moisture in capillary-porous bodies.

With nonisothermal moisture transfer where the regime of heating of the moist material gives rise not only to the moisture-content gradient in it but also to the temperature gradient, moisture will move inside the material due to both the moisture-content gradient (moisture conduction, or concentration diffusion) and the temperature gradient (thermal moisture conduction, or thermal diffusion). This fundamental work of the young scientist became widely known in the USSR and abroad. It was reported at the meeting of a section of the London Royal Society and published in its minutes. In the literature, thermal moisture conduction is known as the Luikov effect. It is similar to thermal diffusion in gases and solutions (the Soret effect). In 1935 A. V. Luikov successfully defended a candidate's dissertation on the same topic.

Moisture motion by the action of the temperature gradient (thermal moisture conduction) in colloidal and capillary-porous bodies is a complex process that includes the following phenomena:

1) molecular thermal diffusion of moisture, mainly in the form of the molecular flow of vapor, resulting from different velocities of the molecules of heated and cold layers of the material;

2) capillary conduction due to the variation in the capillary potential dependent on the surface tension, which decreases with increasing temperature, and since the capillary pressure above a concave meniscus is negative, the pressure decrease increases the suction force, causing moisture in the form of liquid to go off from heated layers of the body and to colder ones;

3) moisture motion by the action of "entrapped" air, since when the material is heated, air in pores expands and pushes liquid to layers with a lower temperature.

Thermal moisture conduction is the reason for the moisture motion in the direction of the heat flow. However, in convective drying a temperature gradient opposite to the moisture-content gradient is set up, which hinders moisture displacement from the inside to the surface of the material. But if directions of the moisture-content and temperature gradients are the same, the same are also directions of the corresponding moisture flows which, taken together, give the total moisture flow. The thermal gradient coefficient introduced by A. V. Luikov shows what moisture-content difference is set up in the material when the temperature difference is $1^{o}C$.

A. V. Luikov demonstrated that the thermal gradient coefficient depends on the moisture content of the material, i.e., on the thermal motion of moisture, and, just like moisture conduction, is specified by the form of the moisture binding with the material.

Proceeding from the phenomena of moisture conduction and thermal moisture conduction A. V. Luikov revealed the mechanism of shrinkage and cracking of the material in drying as well as of transfer of water-soluble substances and showed that the major obstacle to rapid drying of many materials is their cracking. The reason for cracking (local destruction) and for complete destruction (loss of structural integrity) is the development of the volume-stressed state of the dried material above the allowable one specified by the material strength. The stressed state is set up by inadmissible shrinkage resulting from a nonuniform moisture-content and temperature distribution inside the material. Therefore, the main cause of cracking in drying is the presence of moisture-content and temperature fields with appreciable differences of the involved quantities.

Using these phenomena A. V. Luikov introduced the cracking criterion. Knowing the allowable value of the cracking criterion it is always possible to produce a high-grade dried material.

The theory of transfer of water-soluble substances developed by A. V. Luikov allows controlling this process. In many materials, liquid contains soluble substances that are transferred with liquid while it moves and concentrate on the material surface as a result of the liquid evaporation. It should be noted that this is undesirable for some materials and is a necessary condition for other technological processes and materials.

An especially efficient method of controlling the substance transfer is changing the temperature gradient inside the material. By changing the magnitude and direction of ∇t it is possible to set up diverse conditions for the moisture motion and thus influence the physicochemical and biological properties of the material.

A. V. Luikov developed experimental methods for determining specific mass capacity, moisture transfer potentials, moisture conductivity, and thermal moisture conductivity.

The entire experimental and theoretical material on the drying mechanism accumulated in the prewar period was systematized by A. V. Luikov, and in 1938 it was published in the monograph "Kinetics and Dynamics of Drying and Humidification."

While working on general problems of heat and mass transfer, Aleksei Vasilievich, specifically, devoted himself to the theory of heat conduction and the development of efficient techniques for solving problems of unsteady heat conduction using the Laplace–Heaviside operational method. He obtained several new important relationships in the operational calculus. They allow one to solve boundary-value problems of the theory of heat conduction management with only simple algebraic techniques and elements of mathematical analysis.

The wide use of operational methods made it possible to obtain a solution of two forms: one is more convenient for calculations at small Fourier numbers and the other at large ones.

The connection between the similarity theory (the theory of generalized variables) and the operational calculus was established. Thus, solutions acquired a concrete physical meaning.

A method of asymptotic estimates relying on analytical properties of the Laplace transform was worked out. A single sign of the regular mode of heating and cooling of solids was determined, which unified the existing signs of the regular mode of the first, second, and third kind.

A. V. Luikov devised a novel method for solving nonlinear problems of the theory of heat conduction where thermal physical characteristics are dependent on coordinates. From this generalized method, several well-known methods for solving problems of this kind ensue as a special case. This voluminous series of studies was unified in the now classic book "Theory of Heat Conduction," which ran into two editions in the USSR and was translated in many countries.

Strenuous creative work took its toll — A. V. Luikov fell seriously ill and underwent a complicated surgery. Bedridden but preserving fortitude, Aleksei Vasilievich continued to work persistently and fruitfully. He wrote two monographs — one on drying kinetics and dynamics and the other on heat conduction and diffusion.

After recovery, in 1939 A. V. Luikov defended a doctoral dissertation at the Moscow Power Institute. In 1940 he received the title of professor and from 1942 headed the Physics Department of the Moscow Technological Institute of the Food Industry. Here and at the Physics Department of the Moscow Institute of Chemical Engineering, which he headed also, well-equipped research laboratories of molecular physics and theory of heat were established. In them there were carried out extensive investigations of heat and mass transfer in capillary-porous bodies in phase and chemical transformations as well as works on radiative heat transfer and transfer phenomena in a high vacuum that became widely known.

In that period, the international prestige of A. V. Luikov grew — on recommendation of Prof. V. Ostwald, Aleksei Vasilievich was elected a member of the international society Kolloidsgesellschaft

In 1951, A. V. Luikov published the monograph "Drying Theory," and in 1956 he published the second monograph, also concerned with drying problems, "Heat and Mass Transfer in Drying Processes."

The gist of "Drying Theory" is combined heat and moisture transfer in moist material during their interaction with heated gases and hot surfaces and also in the processes of irradiation with thermal and electromagnetic waves in the presence of phase transformations.

Drying theory is an important division of the science of heat and mass transfer. However, drying of moist materials is simultaneously a technological process in which, as was noted above, structural mechanical, technological, and biochemical properties of the material change, since drying involves a change of the forms of moisture binding with the material and partial moisture removal by evaporation. Therefore, drying theory rests not only on the processes of heat and mass transfer in capillary-porous bodies but also on the science of the forms of moisture binding with moist materials.

A. V. Luikov divided all moist materials according to their basic colloidal physical properties into three types:

1. *Typical colloidal bodies.* When moisture is removed, they appreciably change in size (shrink) but retain their elastic properties (e.g., gelatin and pressed flour dough).

2. *Capillary-porous bodies.* When moisture is removed, they become fragile, are contracted slightly, and can be transformed into powder (e.g., sand and charcoal).

3. *Capillary-porous bodies possessing the properties of the first two types.* Among them are most of the materials being dried. Based on an analysis of the forms of moisture binding with the material (by P. A. Rehbinder's scheme) and on the classification of moist materials, A. V. Luikov attempted to elucidate the shape of drying rate curves from the viewpoint of moisture transfer in bodies.

Using drying rate curves A. V. Luikov developed approximate methods of calculating the drying time, which determine the relationship between moisture content of the body and time. This relationship can be obtained by solving a system of differential equations of heat and mass transfer, for which purpose the relation of transfer coefficients to moisture content and temperature should be known. The solution was analytically complicated; therefore A. V. Luikov proposed a fairly reliable equation describing the drying curve with a minimum number of constants determined experimentally.

This calculating procedure has for many years proved to be justifiable for various drying conditions. The essence of the procedure lay in the actual drying curves being approximated by a straight line, i.e., the relationship between the drying rate and the removed moisture came to be directly proportional, and in this case the equation for the drying curve was markedly simplified. At the present time, there are numerous data on the drying coefficient entering into the approximate drying equation.

A further development of the theory of drying kinetics was determining the relationship between heat transfer and mass transfer using a dimensionless quantity that in the basic equation of drying kinetics was called the Rehbinder number.

On the basis of experimental data pertaining to the dependence of the Rehbinder number on moisture content, approximate methods were devised for calculating the average integral temperature of the material that needs to be known for designing the drying process, since the material temperature is in many cases a governing factor.

A. V. Luikov paid much attention to developing the theory of sublimation drying. Some materials should be dried at a low temperature, since even an insignificant rise causes a marked deterioration of their technological properties. Drying at low temperatures and atmospheric pressure proceeds very slowly. Therefore, in order to enhance the process, vacuum drying is used. A pressure decrease sharply increases the evaporation rate by raising the mass transfer coefficient, which in a first approximation is inversely proportional to pressure.

In sublimation drying, the material is in a frozen state. A. V. Luikov's theoretical and experimental investigations in the area of external and internal heat and mass transfer in sublimation drying allowed him to put forward the hypothesis that ice particles are carried away from the surface, which evaporate and thus enhance heat and mass transfer.

Through A. V. Luikov's efforts, a unified theory of combined heat and moisture transfer was created. The principles of diffusive and effusive moisture transport were established, and the effect of molar moisture transfer due to thermal and diffusive creep was proved. As a result, the law of mass transfer in capillary-porous bodies was formulated for nonisothermal conditions.

A. V. Luikov's system of differential equations for combined heat and moisture transfer with account for phase transformations in a unidimensional case is of the form

$$c\rho_0 \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \varepsilon \rho_0 Q \frac{\partial u}{\partial \tau}, \qquad \frac{\partial u}{\partial \tau} = \frac{\partial}{\partial x}\left(a_m \frac{\partial u}{\partial x} + a_m \delta \frac{\partial T}{\partial x}\right),$$

where T is the temperature, u is the moisture content, a_m is the moisture diffusivity, δ is the thermal gradient coefficient, λ is the thermal conductivity, c is the specific heat, ρ_0 is the density of the dry body, ε is the ratio of the variation in the moisture content due to evaporation to the total variation in the moisture content, and Q is the heat of vaporization.

Thus, A. V. Luikov laid the theoretical foundations of combined heat and mass exchange of capillary-porous bodies with the surroundings and determined dimensionless groups and numbers of such processes, and on the basis of A. V. Luikov's extensive and multitudinous studies the modern theory of drying of moist materials was developed.

A. V. Luikov was one of the first to give attention to the fact that, with preset conditions on the body surface (which are frequently very close to actual ones), the use of the Newton law for expressing the specific heat flux q in terms of the temperature difference $(T_w - T_\infty)$

$$q = \alpha (T_w - T_\infty) = \mathrm{Nu} \frac{\lambda}{l} (T_w - T_\infty) ,$$

and hence the heat transfer coefficient α is not always acceptable. He showed that the dependence of the wall temperature on coordinates and time cannot be specified *a priori* but instead should be obtained by simultaneously solving equations of heat propagation in the liquid and body and equations of motion, with temperatures and heat fluxes on the solid–liquid interface being equal, i.e., a so-called conjugate problem of heat transfer should be solved. In such a formulation, the mutual thermal influence of the body and liquid is taken into account, while in another formulation it was disregarded, which is why heat transfer appeared to be independent of properties of the body, its thermal physical characteristics, dimensions, distribution of sources in it, etc., which contradicts the physical sense. It is especially important to consider heat transfer problems as conjugate when heat transfer is unsteady. Indeed, even for the case of limiting values of thermal conductivity of the solid, the surface temperature should be regarded as constant, since while being independent of the coordinates of the surface points it varies over time. However, unlike steady heat transfer, even in this limiting case the law of time variation of the surface temperature cannot be specified beforehand; therefore, all problems of unsteady convective heat transfer should be formulated as conjugate.

The solution of conjugate problems of heat transfer involves serious mathematical difficulties. One of them is that, for example, for stationary problems, even differential equations of different types are encountered: a parabolic partial different equation is obtained for a liquid and an elliptic equation is obtained for a solid.

A. V. Luikov actively and directly participated in the development of novel analytical and numerical methods for solving conjugate problems. The conjugate formulation of heat transfer problems is now a generally accepted approach to solving scientific and practical problems.

A. V. Luikov for the first time generalized Prigogine's principle of the rate of entropy variation during transfer. As a result, a new system of linear equations of transfer was obtained, which differs from the Onsager system in that the flows depend not only on thermodynamic motive forces but also on the rate of their variation.

From this system of correlation follow transfer equations with account for the finite velocity of the substance propagation, and afterward hyperbolic differential equations of heat conduction and diffusion are derived as a special case.

In the last years of his life, Aleksei Vasilievich was captivated by the range of problems that was conventionally called nonlinear thermomechanics. It included problems of thermomechanics and thermodynamics of media with complicated properties, such as micropolar media with memory of various types, primarily the theory of heat conduction with memory. As to the latter, he was first of all interested in the generalizations and thermodynamic substantiation of the hyperbolic equation of heat conduction.

A. V. Luikov and his pupils for the first time proved compatibility of the hyperbolic equation of heat conduction with the second law of thermodynamics, or, in other words, the thermodynamic admissibility of this equation. Subsequently the technique of finding thermodynamic restrictions of the relaxation function was extended to various classes of media with memory and to accounting for all types of relaxation including cross effects. Thus, for example, for a deformable heat conducting medium with memory there are three types of relaxation as to temperature, temperature gradient, and deformation gradient for three independent variables (internal energy, heat flux, and stress tensor). The combination of all the three types of relaxation for each of the three variables gives nine relaxation functions R_{nm} in which three additional elements describe basic types of relaxation (internal energy–temperature, heat flux–temperature gradient, and stress tensor–deformation gradient), and the others are cross ones. Further on these results were extended to the case of generalized thermodynamic systems, and for a linear system they were proved to be sufficient for the fulfillment of the second law in the standard formulation.

For over 40 years of his scientific research work, A. V. Luikov published about 250 scientific papers and 18 monographs, including "Drying Theory," "Transfer Phenomena in Capillary-Porous Bodies," "Theory of Heat Conduction," "Theory of Energy and Substance Transfer," "Reference Book on Heat and Mass Transfer," etc.

His monographs were translated and published in England, Germany, France, Hungary, the U.S., and other countries. In 1951, he was awarded the State Prize of first degree for the monograph "Drying Theory" (1959), and in 1969, for the monograph "Theory of Heat Conduction" he was honored with the highest award in the USSR in the area of thermal engineering — the I. I. Polzunov Prize.

Possessing a keen sense of the new, an exceptional capacity for work, and self-discipline, Aleksei Vasilievich valued these qualities in people — his colleagues and pupils. He drew the talented youth in the solution of complex problems, encouraging their creative growth in every possible way, trusted them, and fearlessly promoted them to the leadership over important segments of work. He constantly reminded them that a critical analysis of basic concepts underlying the theory was always useful and necessary, that even a seemingly absurd idea should not be immediately and categorically rejected, since only the presence of plenty of new ideas originated by "mental" experiments can lead to the successful development of science and engineering. The Department of Thermal Physics (now of Power Physics) established by him at the Belarusian State University trains highly qualified specialists-researchers in various areas of the science of heat and mass transfer. For 40 years Aleksei Vasilievich taught at higher educational institutions and guided the work of graduate students and competitors. He trained 130 candidates of sciences; 27 his pupils became doctors of sciences.

Exceptionally fruitful was the activity of A. V. Luikov as the director of the Heat and Mass Transfer Institute of the BSSR Academy of Sciences which he headed in 1956. In a short time, a small team grew to a large thermal physical scientific center that can be regarded as an actual heritage of A. V. Luikov. The traditions laid by A. V. Luikov at the Institute were unique. Democratism reigning at the Institute played a decisive role in the formation of the special creative tenor that predetermined the creation of an atmosphere of free discussions organically combining with open and benevolent critique and the aptitude to rejoice at the successes of colleagues. From the Heat and Mass Transfer Institute evolved the Institute of Nuclear Power Engineering of the BSSR Academy of Sciences, the Institute of Water Problems of the Ministry of Land Improvement and Water Conservation of the USSR, and the Belarusian branch of the G. M. Krzhizhanovskiy Power Institute. In 1969, for great scientific achievements and successes in training scientific cadre the Institute was honored with a high government award — Order of the Red Banner of Labor.

On the initiative of A. V. Luikov, in 1958 "Inzhenerno-Fizicheskii Zhurnal" was founded; A. V. Luikov was its editor-in-chief the end of his life. In 1959, A. V. Luikov was appointed the USSR editor of the International Journal of Heat and Mass Transfer, and he was vice chairman of the Soviet National Committee for Heat and Mass Transfer.

A. V. Luikov's large contribution to thermal physics won deserved recognition. In 1956 he was elected Academician of the BSSR Academy of Sciences, and in 1957, Member of the USSR Academy of Architecture and Civil Engineering. At the same time, the title of Honored Worker of Science and Engineering of the RSFSR was conferred on him. In 1967 he received the highest award of the country — Order of Lenin — and in 1970, Order of the Red Banner of Labor.

A. V. Luikov attached great importance to the international cooperation of scientists and continually strove for its strengthening. He initiated All-Union Conferences on Heat and Mass Transfer which were held at the Institute from 1961 every four years. From 1988, these have been International Forums whose participants are hundreds of scientists from various countries. It is not accidental that the IV International Forum on Heat and Mass Transfer held in May 2000 was dedicated to the 90th anniversary of A. V. Luikov.

A. V. Luikov's services in reinforcing international relations of scientists have been recognized in many countries of the world. In 1969 A. V. Luikov was elected honored foreign member of the Society of Mechanics of the Polish Academy of Sciences, in 1971 the government of the Czech Republic decorated him with a Gold Medal for Services in the Development of Friendship and Cooperation with the Czechoslovak Socialist Republic for his contribution to the progress of science of heat and mass transfer, and in 1973 A. V. Luikov was decorated with a Gold Medal of the French Institute of Fuel and Energy.

The distinctive talent, earnest service to science, respect and love for people, devotion to correct scientific principles — all this taken together earned Aleksei Vasilievich Luikov wide recognition as a public and political figure, one of the leading scientists-thermal physicists.

O. G. Martynenko