Journal of Engineering Physics and Thermophysics, Vol. 73, No. 5, 2000

A. V. LUIKOV'S SCIENTIFIC LEGACY (ON THE 90TH ANNIVERSARY OF HIS BIRTH)

The search in science is endless; therefore for a true scientist the discovery of a new phenomenon does not become the conclusion of his work. It lays the foundation for the beginning of new research, a new field of knowledge. And then – a new road to the unknown ... .

It is exactly this kind of person, a constantly searching scientist, that Academician Aleksei Vasil'evich Luikov was. He would have turned 90 in September of this year.

He left a deep imprint in science as well as an indelible memory in the minds and hearts of his comrades-in-arms and disciples.

Aleksei Vasil'evich Luikov was born in 1910 in Kostroma. After his graduation from the Physicomathematical Department of the Yaroslavl' Pedagogical Institute in 1930, he worked in Yaroslavl' as a teacher at the Power Engineering Faculty for Workers, and then as a research worker at the Drying Laboratory of the All-Union Heat Engineering Institute. Here he conducted his first investigations into the kinetics of drying and the development of methods of determining the thermophysical characteristics of moist materials. In 1931 he received his first inventor's certificate for his invention "Alternating-Pressure Dryer" for work completed on the dehydration of moist porous materials at alternating vapor pressure.

Beginning in 1931, A. V. Luikov developed rapid methods for comprehensive determination of thermophysical characteristics from one short experiment. They were used to discover and to study the anisotropy of heat conduction of dispersed materials and polymer solutions due to the flow. It was demonstrated that flowing systems with a slowly obliterating or infinitely large mechanical memory that contain extended elements (linear macromolecules, solid particles), acquire tensor heat conduction as a result of flow. The components of the thermal-conductivity tensor differ from their isotropic analog by 200–300%.

As early as in 1932, to analyze the kinetics and dynamics of the process of drying, A. V. Luikov conducted experiments to investigate the moisture-content fields in convective drying of capillary-porous bodies (filter paper disks). As a result he discovered the salient points of the curves of distribution of the moisture content across the thickness of the body that corresponded to the site of the location of the evaporation surface. At the same time it was established from the analysis of the moisture-content fields that there was no sharp line of demarcation between the evaporation surface and the subsequent layers similarly to the frost line of the ground in the Stefan problem. Thus, one can say that the evaporation occurs not only on the deepened surface but also over the entire thickness of the body. However, the largest quantity of the evaporating liquid escapes from the evaporation surface. In another method, to investigate the deepening of the evaporation zone, use was made of the temperature fields experimentally obtained in the process of drying of moist materials. If the temperature of bodies is measured at several points, there is observed a salient point of the curve (starting from this instant the temperature t increases sharply) as the evaporation zone passes through the point x_i on the

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute," National Academy of Sciences of Belarus, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 5, pp. 883-892, September–October, 2000.

1062-0125/00/7305-0869$25.00 ©2000 Kluwer Academic/Plenum Publishers

curve $t = f(x)$. By recording these salient points for each instant, Luikov obtained a relationship between the thickness of the evaporation zone and the time and showed that the evaporation zone deepens into the body approximately by a linear law.

On the basis of the experiments conducted, A. V. Luikov was the first to propose temperature curves for the analysis of the kinetics of a drying process, including the study of the mechanism of deepening of the evaporation zone.

In 1932, Aleksei Vasil'evich enrolled in the post-graduate school at the Scientific-Research Institute of Moscow University, where at that time worked well-known scientists – A. P. Mlodzeyevskii, I. V. Luzin, A. S. Predvoditelev, I. E. Tamm, and others who had a great influence on the formation of his creative abilities and further scientific activities.

In 1932–1935, A. V. Luikov worked long and fruitfully on the problem of transfer in colloidal and capillary-porous bodies. He developed a new method to determine the thermophysical characteristics of moist materials. In 1935, he discovered a new phenomenon – thermal diffusion of moisture in capillary-porous bodies.

In nonisothermal transfer of moisture, when the regime of heating of a moist material determines the appearance of a gradient not only of moisture but also of temperature in it, the moisture inside the material will move both due to the moisture gradient (the phenomenon of moisture conduction, or concentration diffusion) and owing to the temperature gradient (the phenomenon of heat and moisture conduction, or thermal diffusion). This fundamental work by the young scientist became widely known in the USSR and abroad. It was reported at a panel of the London Royal Society and published in its transactions. In the literature, the phenomenon of heat and moisture conduction is known by the name of the Luikov effect. It is similar to the phenomenon of thermal diffusion in gases and solutions (the Soret effect). In 1935, A. V. Luikov successfully defended his dissertation for a candidate's degree (PhD thesis) on this subject.

The motion of moisture under the action of the temperature gradient (heat and moisture conduction) in colloids and capillary-porous bodies is a complex process that includes the following phenomena:

1) molecular thermal diffusion of moisture, basically in the form of a molecular flow of vapor, which occurs due to the different velocity of molecules of the heated and cold layers of the material;

2) capillary conductance determined by the change in the capillary potential that is dependent on the surface tension which decreases as the temperature increases, and since the capillary pressure over the concave meniscus is negative, the decrease of pressure increases the suction force, which causes the moisture in the form of liquid to leave the heated layers of the body for the colder ones;

3) the movement of the moisture under the action of the "entrapped" air, since during the heating of the material the air in the pores expands and pushes the liquid toward the layers with a lower temperature.

Heat and moisture conduction is the reason for the movement of the moisture toward the heat flux. However, during convective drying there develops a temperature gradient opposite to the moisture gradient, which prevents the movement of the moisture from inside toward the surface of the material. But if the directions of the moisture gradient and the temperature gradient coincide, the directions of the corresponding moisture flows coincide, too, yielding, on the whole, a total moisture flow. The thermogradient coefficient introduced by A. V. Luikov shows what moisture-content difference is created in the material at a temperature difference of $1^{\circ}C$.

A. V. Luikov showed that the thermogradient coefficient depends on the humidity of the material, i.e., on the thermal movement of moisture, and, just as moisture conduction, is determined by the form of the moisture's bond with the material.

Based on the phenomena of moisture conduction and heat and moisture conduction, A. V. Luikov revealed the mechanism of the shrinkage and cracking of the material in the process of drying as well as of the transfer of water-soluble substances and showed that the main obstacle to fast drying of many materials is their cracking. The reason for the appearance of cracks (local fracture) as well as of total destruction (loss of structural integrity) is the development of the volume stressed state of the dried material above the maximum permissible level determined by the strength of the material. This stressed state is created by inadmissible shrinkage that, in turn, appears as a result of the nonuniform distribution of the moisture content and temperature inside the material. Hence, the main cause of cracking in the process of drying is the presence of the moisture-content and temperature fields with significant differences of these quantities.

Using these phenomena, A. V. Luikov introduced the criterion of crack formation. Knowing the permissible value of the criterion of crack formation, it is always possible to obtain dried material of high quality.

The theory of transfer of water-soluble substances, developed by A. V. Luikov, makes it possible to control this process. The liquid in many materials contains soluble substances that, as the liquid moves, are transferred with it and concentrate on the surface of the material due to the evaporation of the liquid. It should be noted that this is undesirable for some materials, whereas it is an indispensable condition for other technological processes.

The change of the temperature gradient inside the material is a particularly efficient method of control over the transfer of a substance. By changing the magnitude and direction of ∇t, it is possible to create diverse conditions for the transfer of moisture and by doing so to act upon the physicochemical and biological properties of the material.

A. V. Luikov created experimental methods to determine the specific mass capacity, the moisture-transfer potentials, and the coefficients of moisture conductivity and thermal and moisture conductivity.

All the experimental and theoretical material on the mechanism of the process of drying accumulated in the pre-war period was systematized by A. V. Luikov and was published in 1938 in the monograph "The Kinetics and Dynamics of the Processes of Drying and Moistening."

While working on general problems of heat and mass transfer, Aleksei Vasil'evich, in particular, devoted himself to the theory of heat conduction and to the development of efficient methods of solving problems of nonstationary heat conduction by the Laplace–Heaviside operational method. He obtained a number of important new relationships in the operational calculus. They make it possible to solve complex problems of the theory of heat conduction by using the simple algebraic apparatus and elements of mathematical analysis alone. In particular, he derived a Heaviside expansion formula for the case of multiple roots without using the notion of a contour integral in the region of complex variables.

The wide use of operational methods made it possible to obtain a solution in two forms: one convenient for calculations at small values of the Fourier numbers, the other – for large values of the Fourier numbers.

A link was established between the theory of similarity (the theory of generalized variables) and the operational calculus. Thus, the solutions acquire a concrete physical meaning.

The method of asymptotic evaluations based on the analytical properties of the Laplace transform was developed. A unified sign was established for the regular regime of heating or cooling of solids that combines the existing signs of the regular regime of the first, second, and third kind.

For the first time in the theory of heat conduction the so-called boundary conditions of the fourth kind were introduced, for which a number of problems were solved. In their works, A. V. Luikov and his disciples showed that a rigorous formulation of problems of convective heat exchange in the interaction of the bodies' surface with the environment corresponds to the boundary conditions not of the third kind, as was usually assumed earlier, but of the fourth one. Thus, the boundary conditions of the fourth kind acquire quite an important and topical significance in the theory of convective heat exchange.

A. V. Luikov developed a new method of solving nonlinear problems of the theory of heat conduction, when thermophysical characteristics depend on the coordinates. This generalized method results as a particular case in a number of well-known methods of solving this kind of problem. This extensive cycle of works was generalized in A. V. Luikov's now classical book "Theory of Heat Conductions," which went through two editions in the USSR and was translated in many countries.

This strenuous creative work took its toll on A. V. Luikov's health – he was taken seriously ill and put through a complicated operation. Restricted to his bed but preserving moral tenacity, Aleksei Vasil'evich continued to work fruitfully by hand; he wrote two monographs – one on the kinetics and dynamics of drying processes (40 printed sheets per volume), the other – on heat conduction and diffusion.

After recovering in 1939, A. V. Luikov defended a dissertation for a doctoral degree at the Moscow Power Engineering Institute. In 1960 he was confirmed in the title of professor. Since 1942 he had been in charge of the Department of Physics at the Moscow Technological Institute for the Food Industry. Well-equipped research laboratories for molecular physics and the theory of heat were established there, as well as at the Department of Physics of the Moscow Institute of Chemical Machine-Building that he also headed, combining these two jobs. These laboratories performed extensive widely publicized research into heat and mass transfer in dispersed and capillary-porous bodies during phase and chemical transformations, as well as work on radiation heat transfer and the phenomena of transfer in deep vacuum.

At the same time, Luikov's international authority as a scientist also grew – on the presentation by Prof. V. Ostwald Aleksei Vasil'evich, he was elected member of the international society Kolloidgesellschaft.

In 1951, A. V. Luikov published the monograph "Theory of Drying," and in 1956 he published a second monograph, also devoted to problems of drying – "Heat and Mass Transfer in Processes of Drying."

The basis of the "Theory of Drying" is the regularities of an interrelated heat and moisture transfer in moist materials during their interaction with heated gases and hot surfaces, as well as in processes of irradiation with heat and electromagnetic waves in the case of phase transformations.

The theory of drying is an important section of the science on heat and mass transfer. However, the process of drying of moist materials is, at the same time, a technological process during which, as was indicated above, changes occur in the structural-mechanical, technological, and biochemical properties of the material due to the fact that in the process of drying a change in the forms of the moisture's bond with the material and its partial removal through evaporation. Therefore, the theory of drying, too, is based not only on the processes of heat and mass transfer in the capillary-porous bodies but also on the doctrine of forms of the moisture bond with moist materials.

A. V. Luikov divided all moist materials into three types, depending on their basic colloidal-physical properties:

1. Typical colloidal bodies. As moisture is removed they significantly change their size (shrink) but preserve their elastic properties (gelatin, pressed flour dough).

2. Capillary-porous bodies. As moisture is removed they become brittle, always incompressible, and can be turned into powder (sand, charcoal).

3. Capillary-porous colloidal bodies that possess the properties of the first two types. They include the majority of materials that are subjected to drying.

On the basis of analysis of the forms of the moisture bond with a material and of the classification of moist materials, A. V. Luikov made an attempt to explain the shape of the drying-rate curves from the point of view of the mechanism of moisture transfer in bodies.

Using the drying-rate curves, A. V. Luikov developed approximate methods for calculating the duration of a drying process that establish the relationship between the body's moisture content and time. This relationship can be obtained by the solution of a system of differential equations for heat and mass transfer, which makes it necessary to know the relationship of the transfer coefficients with the moisture content and temperature. The solution turns out to be analytically complex; therefore, A. V. Luikov proposed a sufficiently reliable equation that describes a drying curve with a minimum number of constants determined experimentally.

For many years this method of calculation justified itself well for different conditions of drying. The essence of the method was that the actual drying-rate curves are approximated by a straight line with a minimum possible error, thus resulting in a directly proportional relationship between the rate of drying and the moisture being removed, and in this case the drying-curve equation was significantly simplified. At present there are numerous data on the drying coefficient that are included in the approximate drying equation.

A further step in the development of the theory of the kinetics of a drying process was the establishment of the interrelationship between heat exchange and mass exchange using a dimensionless quantity, which was called the Rebinder number in the basic equation of the kinetics of drying.

Based on the experimental material on the dependence of the Rebinder number on moisture content, approximate methods were developed for calculating the average integral temperature of the material, knowledge of which is necessary to create a drying technology since the temperature of the material is in many cases a determining factor.

A. V. Luikov paid a great deal of attention to the development of the theory of sublimation drying. Certain materials require drying at low temperature since an insignificant rise in it causes a sharp deterioration of their technological properties. Low-temperature drying at atmospheric pressure occurs very slowly. Therefore, to intensify the process, vacuum drying is used. Reducing pressure sharply increases the intensity of evaporation by raising the mass-transfer coefficient, which as 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 works in the field of external and internal heat and mass transfer during sublimation drying allowed him to propose a hypothesis on the removal of ice particles from the surface that evaporate and thus contribute to the increase in the value of the heat- and mass-transfer coefficients.

A. V. Luikov's works created a unified theory of interrelated heat and mass transfer in capillary-porous bodies. They established the regularities of the diffusion and effusion transport of moisture and proved the great influence of the molar transfer of moisture caused by thermal and diffusion slip. As a result, a law was formulated for mass transfer in capillary-porous bodies for nonisothermal conditions.

These regularities allow a rather strict substantiation of the change in the thermophysical and hydrometric characteristics as functions of the moisture content of the body. A. V. Luikov's system of differential equations

$$\frac{\partial T}{\partial \tau} = k_{11} \nabla^2 T + k_{12} \nabla^2 U \ ,$$

$$\frac{\partial U}{\partial \tau} = k_{22} \nabla^2 U + k_{21} \nabla^2 T$$

is at present solved for a broad range of problems and various boundary conditions. When these equations are derived it is expected that the heat- and mass-transfer coefficients and the thermodynamic characteristics do not depend on the coordinates. Furthermore, it is considered that the temperature of the moisture in the capillaries of the body equals the temperature of the capillaries' walls during the entire process of heat and mass transfer, which is true only for diffusion transfer.

Thus, A. V. Luikov laid the theoretical foundations of interrelated heat and mass exchange of capillary-porous bodies with the environment; he established criteria and similarity numbers of these processes, and his numerous extensive investigations have served as a basis for the contemporary theory of drying of moist materials.

A. V. Luikov was among the first to note that use of the Newton law is unacceptable for the expression of the specific heat flux q through the temperature head $(T_w - T_\infty)$

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

and hence the heat-transfer coefficient a, too, for pre-assigned variable conditions on the surface of the body (often very close to the actual ones). He showed that the law of the dependence of the wall's temperature on the coordinates and time cannot be assigned a priori but must be obtained through a simultaneous solution of equations of the propagation of heat in a liquid and in a solid together with the equations of motion, with the temperature and heat fluxes being equal at the solid–liquid boundary, i.e., the so-called conjugate problem of heat transfer must be solved. In this formulation allowance is made for the mutual thermal influence of the body and the liquid which is not taken into account in a different formulation, resulting in the heat transfer being independent of the properties of the body, its thermophysical characteristics, dimensions, distribution of the sources in the body etc., which contradicts the physical meaning. It is especially important to consider the heat-transfer problems as conjugate ones in nonstationary heat transfer. Indeed, even for the case of maximum values of the thermal conductivity coefficient of a solid body, the temperature of the body's surface cannot be considered to be constant since, although it indeed does not depend on the coordinates of the surface points, it changes with time. However, in contrast to stationary heat transfer, even in this limiting case the law of change in the surface temperature with time cannot be assigned in advance, and, hence, practically all the problems of nonstationary convective heat transfer must be formulated as conjugate ones.

The solution of conjugate heat-transfer problems involves serious mathematical difficulties. One of them is that, for example, for stationary problems one has to deal with differential equations of various types: for a liquid one ends up with an equation in partial derivatives of parabolic type, and for a solid body, of elliptical type.

A. V. Luikov took an active and direct part in the development of new analytical and numerical methods and operational techniques of solving conjugate problems. At present, the conjugate formulation of heat-transfer problems is a universally recognized approach toward the solution of scientific and practical problems.

A. V. Luikov was the first to give a generalization of the Prigogine principle on the rate of change in the entropy in a transfer process. As a result, a new system of linear equations of transfer was obtained that differed from the Onsager system in that the flows depend not only on the thermodynamic driving forces but also on the rate of their change and on the time derivatives of the flows.

From this system of generalized relations follow transfer equations with allowance made for the final velocity of propagation of the substance, and after that as a particular case hyperbolic differential equations of heat conduction and diffusion are derived.

In the last years of his life Aleksei Vasil'evich had, among other things, a profound enthusiasm for a set of problems that was conventionally referred to as "nonlinear thermodynamics." Included here were questions of the thermomechanics and thermodynamics of media with complicated properties: such as micropolar media, media with memory of various types, first of all – the theory of heat conduction with memory. In the latter he was above all interested in the generalizations and the thermodynamic substantiation of the hyperbolic equation of heat conduction.

A. V. Luikov and his followers were the first to prove the compatibility of the hyperbolic equation of heat conduction with the second principle of thermodynamics or, in other words, the thermodynamic assumption of this equation. Later on, the technique of finding thermodynamic limitations of the relaxation function was generalized to different classes of media with memory, as well as to the case of taking account of all types of relaxation, including the cross effects too. Thus, for example, for a deformable heat-conducting medium with memory there are three types of relaxation, by temperature, by the temperature gradient, and by the deformation gradient, for three independent variables (the internal energy, the heat flux, and the stress tensor). The combination of all three types of relaxation for each of the three variables yields nine relaxation functions R_{nm}, in which three additional elements describe the main types of relaxation (internal energy – temperature, heat flux – temperature gradient, stress tensor – deformation gradient); the rest are cross types.

These results were later developed for the case of generalized thermodynamic systems, and for the linear theory their sufficiency for the feasibility of the second principle in standard formulation was also proved. Thus, the problem of thermodynamic limitations in the linear theory was fully solved.

During the more than 40 years of his scientific-research work, A. V. Luikov published about 250 scientific papers and 18 monographs, including "The Theory of Drying," "Transfer Phenomena in Capillary-Porous Bodies," "The Theory of Heat Conduction," "The Theory of Energy and Material Transfer," "The Handbook of Heat and Mass Transfer," etc.

His monographs were translated and were published in England, Germany, France, Hungary, the USA, and other countries. In 1951, A. V. Luikov was awarded a state prize of the first degree for his monograph "The Theory of Drying" (1950), and in 1969 he was awarded the supreme prize of the USSR in the field of heat engineering – an I. I. Polzunov prize.

Having a highly developed feeling of the new and an exceptional industriousness and self-discipline, Aleksei Vasil'evich appreciated these qualities in people – colleagues and disciples. He invited talented young people to participate in the solution of complex problems, contributing to their creative development, trusting them, and bravely promoting them to the leadership of important sections of work. He kept reminding them of his view that critical analysis of the main notions lying at the foundation of a theory is always beneficial and necessary, that even a seemingly absurd idea must not be immediately and categorically rejected since only the presence of a plurality of new ideas borne by "mental experiments" is the greatest condition for the development of science and engineering.

The Department of Thermal Physics that he set up at the Belarusian State University prepares highly qualified specialists-researchers in various fields of the science on heat and mass transfer. For 40 years Aleksei Vasil'evich taught at higher educational establishments and supervised the work of full time and part time postgraduate students. He prepared 130 Candidates of Sciences (PhD degree holders), and 27 of his disciples became Doctors of Sciences.

A. V. Luikov's work in his position as Director of the Institute of Heat and Mass Transfer (IHMT) of the BSSR Academy of Sciences, of which he became head in 1956, was exceptionally fruitful. Within a short period of time a small team of 30 people grew to become a major thermophysical scientific center. The IHMT of the BSSR Academy of Sciences branched into the Institute of Nuclear Power Engineering of the BSSR Academy of Sciences, the Institute of Water Problems of the Ministry of Water Resources of the USSR, and the Belarusian Branch of the A. M. Krzhizhanovskii Power Engineering Institute. In 1969, the Institute was awarded a high Government award – the Order of the Red Banner of Labor for great scientific achievements and success in the preparation of scientists.

In 1958, at A. V. Luikov's initiative, the "Inzhenerno-Fizicheskii Zhurnal" was set up, and he remained its editor-in-chief till the end of his life. In 1959, Luikov was appointed editor of the "International Journal of Heat and Mass Transfer" on behalf of the USSR; he was Deputy Chairman of the Soviet National Committee on Heat and Mass Transfer.

A. V. Luikov's great contribution to thermal physics enjoyed deserved recognition. In 1956 he was elected Member of the BSSR Academy of Sciences, in 1957 – full Member of the USSR Academy of Construction and Architecture, in 1957 he was awarded the title of Honored Man of Science and Technology of the RSFSR, in 1967 he received the highest decoration of the country – the Order of Lenin, and in 1970 – the Order of the Red Banner of Labor.

A. V. Luikov attached great importance to the international cooperation of scientists and constantly sought its strengthening. At the Institute, he initiated the All-Union Conferences on Heat and Mass Transfer, which have been held every four years here since 1961. Since 1988 they have been International Forums, which are attended by hundreds of scientists from different countries. It is not by accident that the IVth International Forum on Heat and Mass Transfer held last May was dedicated to the 90th anniversary of A. V. Luikov's birth.

A. V. Luikov's services to the strengthening of international ties between scientists have been recognized in many countries of the world. In 1969, he was elected Honorary Foreign Member of the Society of Mechanical Engineers of the Polish Academy of Sciences, in 1971 the Government of the Czechoslovak Republic decorated him with the gold medal "For Services to the Development of Friendship and Cooperation with the CzSSR," and in 1973, he was decorated with the Gold Medal of the French Institute of Fuel and Energy.

His distinctly original talent, devotion to science, respect and love for people, the scientific integrity of a scientist – all this taken together, won wide recognition for Aleksei Vasil'evich Luikov as a public and political figure and one of the leading scientists in thermal physics.

At present, the name of A. V. Luikov has been conferred on the Institute of Heat and Mass Transfer of the Academy of Sciences of the BSSR, which has been turned into a widely known scientific center by his work and the work of his followers.

O. G. MARTYNENKO