IN MEMORY OF A. V. LYKOV, ACADEMICIAN, BELORUSSIAN ACADEMY OF SCIENCES (1910-1974)

O. G. Martynenko

September 20, 1990 is the 80th anniversay of the birth of Aleksei Vasil'evich Lykov, the leading Soviet researcher in thermophysics.

He was born in 1910 in Kostroma, and after graduating from the physics and mathematics section at Yaroslavl Pedagogic Institute in 1930, he started work in the drying laboratory at the Dzerzhinskii All-Union Heat Engineering Institute as an engineering physicist. There he made his first researches on the theory of drying and developed methods of determining thermophysical characteristics for moist materials. In 1931, he obtained his first author's certificate for the invention of a variable-pressure dryer.

Beginning in 1931, he worked on the development of rapid methods of combined determination for thermophysical characteristics from single brief experiments. His methods led to the discovery of thermal conductivity anisotropy in powder materials and polymer solutions, the latter due to flow. Research showed that a flow system with a slowly erased or infinitely retained mechanical memory and containing elongated elements such as linear macromolecules or solid particles on flow is characterized by tensor thermal conduction. The components of the tensor, the thermal conductivities, differ from the isotropic analog by 200-300%.

In 1932, he researched the water-content patterns in convective drying for open-pore bodies (filter paper disks) in order to analyze coupled heat and water transport. He found that there was an inflection on the curve representing the thickness distribution of the water. Those points corresponded to evaporation surfaces. The patterns showed that there was no sharp boundary between the evaporation surface and subsequent layers such as occurs in soil freezing in the Stefan approach. The largest amount of evaporated liquid relates to the evaporation surface, but less rapid evaporation occurs throughout the thickness, decreasing gradually away from the evaporation surface as the surface of the body is approached. It is therefore better to speak of the evaporation zone descending during drying. To examine this, measurements were made on the temperature patterns during drying. If one measures the temperature t at several points, when the evaporation zone passes through point x_i, a kink occurs on the $t_i = f(\tau)$ curve (the temperature starts to rise rapidly). He recorded those points for each instant and derived the time dependence of the evaporation-zone thickness, from which he showed that the zone advanced roughly linearly into the body.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 59, No. 3, pp. 357-364, September, 1990.

0022-0841/90/5903-1071$12.50

In 1932, he registered as a graduate student at the Physics Research Institute at Moscow University, where at that time there were outstanding workers such as A. K. Timiryazev, A. P. Mlodzevskii, I. V. Luzin, A. S. Predvoditelev, and I. E. Tamm, who had a considerable influence in shaping his creative capacity and subsequent activity.

In 1935, he presented his PhD thesis.

In 1933-35, he demonstrated water thermal diffusion, which was an important step in the theory of coupled heat and mass transport. In nonisothermal transport, i.e., when a moist material is heated, one gets not only a temperature gradient but also a water-content gradient, with the water displaced because of the two gradients, the temperature one producing thermal diffusion and the concentration one producing concentration-dependent diffusion. This fundamental result became widely known in the USSR and abroad. It was reported at the Royal Society of London and published in its proceedings. Thermal water diffusion in a moist material has been called the Lykov effect and is similar to thermal diffusion in gases and solutions (the Soret effect).

The water motion due to a temperature gradient (thermal water conduction) in a colloidal or open-pore material is complicated and involves the following:

1) molecular thermal diffusion mainly as the molecular flow of vapor arising because of differences in molecular speed between the hot and cold layers;

2) capillary transfer due to change in the capillary potential, which is dependent on the surface tension, which has a negative temperature coefficient, and as the capillary pressure above a concave meniscus is negative, reduction in the pressure raises the expelling force, so the water in liquid form leaves the hotter layers for the colder ones; and

3) water displacement caused by the trapped air. When the material is heated, the air in the vapor expands and impels the liquid into layers with lower temperatures.

The thermal water conduction is the reason for the displacement along the heat-flux direction. In convective drying, there is a temperature gradient, which is opposite in direction to the water-content gradient, and this hinders water movement from the interior to the surface.

If the water-content and temperature gradients coincide in direction, the corresponding water fluxes also coincide, which together give the total water flux.

Lykov's thermal gradient coefficient indicates how a difference in water contents is produced in a material for a temperature difference of one. He found that it is dependent on the water content, i.e., the thermal displacement, as also the water conduction is related to the way in which the water is bound to the material.

From these phenomena, he elucidated the mechanisms producing shrinkage and cracking during drying, as well as water-soluble substance transport.

A major obstacle to rapid drying in many materials is cracking. Cracks appear (local failure) and complete failure occurs (loss of integral structure) because of the three-dimensional state of strain exceeding the permissible limit related to the strength.

That state of strain results in impermissible shrinkage, which in turn arises from the uneven water-content and temperature distributions.

The main reason for cracking during drying is that there are water-content and temperature patterns involving considerable differences.

On that basis, he introduced a cracking criterion. If the limiting value for it is known, one can always obtain a dried material with good quality.

Lykov's theory of water-soluble substance transport enables one to control the latter.

The liquid in a material may contain soluble substances, which are transported when the liquid moves and accumulates at the surface because of evaporation. In some materials, this is undesirable (e.g., surface darkening), while in others it is necessary (drying in plaster, the transport of bonding agents to surfaces to give firm joints between gypsum and cardboard, and solute transport to nuclei).

A particularly effective method of controlling the transport is to adjust the temperature gradient within the material. The direction and magnitude of $\mathrm{grad}\,T$ can be adjusted to provide various conditions for water displacement, which enables one to influence the physicochemical and biochemical parameters.

He researched solute transport by analyzing the temperature and water-content patterns in model open-pore materials.

His accumulated data on heat and mass-transfer mechanisms were classified and published in 1938 in Drying and Moistening Kinetics and Dynamics.

He continued to work on the general theory of coupled heat and mass transfer and devised methods of determining the specific mass capacity, water-transport potentials, and water conductivity and thermal diffusivity coefficients.

These phenomena and methods he used in formulating equations for the transport in open-pore bodies. The solutions with various boundary conditions give nonstationary patterns.

His stressful creative activities were not without effect on his health: he became seriously ill and underwent a complicated operation. In spite of that, he continued to work vigorously and fruitfully and wrote two books, also in 1939 presenting his D. Sc. thesis and training scientific workers. In 1940, he was appointed Professor. During that period, his international fame increased, and on the initiative of Professor W. Ostwald, he was elected a member of the International Kolloidgesellschaft.

In 1950, he published Drying Theory, and in 1956, Heat and Mass Transfer during Drying. These presented the principles of coupled heat and water transport in materials on interaction with hot gases and heated surfaces and also under irradiation by thermal radiation or electromagnetic waves in the presence of phase transitions. The basic concepts in the science of heat and mass transfer were first clearly formulated there.

His research on heat and mass transfer and on the thermophysical characteristics of nonmetallic materials, which involved new methods of determining transport coefficients, developed particularly rapidly after his transfer in 1954 to the Power Institute, Academy of Sciences of the USSR, where he directed the laboratory of molecular physics and mass transfer.

Drying is not merely a heat-engineering operation, but also a technological process in which the mechanical, technological, and biochemical parameters alter because the binding form of the water is changed and some water is lost by evaporation. Drying theory is therefore based not only on heat and mass transfer in open-pore materials, but also on the forms in which water is bound to the material.

Lykov divided materials into three types on the basis of their major physical properties:

1. Typical colloids. When liquid is removed from these, they change considerably in dimensions (contract) but retain their elasticity (gelatin or pressed flour dough).

2. Open-pore bodies. When liquid is removed, they become brittle and contract only a little, but they may be converted to powders (sand or wood charcoal).

3. Open-pore colloidal materials, which have the properties of the first two types. These include most materials that need to be dried.

The binding forms and the classification were used in explaining the drying-rate curves from the viewpoint of the transport mechanism.

He used the drying curves in approximate methods of calculating drying times, which establish the time dependence of the water content, which can be found by solving the heat and mass transfer equations, for which one needs to know how the transport coefficients are dependent on water content and temperature. An analytic solution is fairly complicated, so he proposed a fairly reliable equation that describes the drying curves with the minimum number of parameters, which can be determined by measurement. That method has been used for many years for determining limiting drying conditions. The essence is that the actual rate curve is fitted with a minimum-error straight line, which gives a directly proportional relationship between the drying rate and the amount of water removed, which means that the equation for the drying curve is simplified considerably. In Drying Theory and in other literature, there is now much numerical evidence on drying coefficients as appearing in the approximate equation.

Further progress was made in drying theory by the establishment of a relation between heat and mass transfer on the basis of the Rebinder number, which appears in the drying equation.

The measured dependence of the Rebinder number on the water content has been used in approximate methods of calculating the mean integral temperature, which is required in drying technology, since the temperature is often the decisive factor.

Lykov also devoted much attention to the theory of freeze drying. Some materials have to be dried at low temperatures because slight rises cause marked deterioration. Low-temperature drying is very slow at atmospheric pressure, so to accelerate the drying, a vacuum is used. The reduced pressure greatly increases the evaporation rate by raising the mass-transfer coefficient, which to a first approximation is inversely proportional to the pressure.

The material in that treatment is in the frozen state.

His researches on external and internal heat and mass transfer in freeze drying provided a hypothesis on the loss of ice particles from the surface, which evaporate and thus raise the heat and mass transfer coefficients.

His researches were used in 1955 in designing and commissioning the first freeze-drying plant in the USSR, which was at Rostov on Don.

His research also involved much attention to drying technology with various heat-input methods.

Drying technology is a major division of drying science. The task is to devise control methods for processes in the material in order to obtain a high-grade product with controlled physicochemical, structural, mechanical, and biochemical parameters.

Such methods involve drying theory.

Properly selected drying modes, e.g., for food grains, should preserve the amount and quality of the gluten; for seed grains, it is important to raise the sprouting and growth energy, while in a microbiological material, one needs to retain the activity, and in a ceramic component, there should be no microcracks or deformation.

The specific features thus impose different specifications on the drying.

In his researches, he always envisaged a close relationship between those tasks and drying theory and technology.

Lykov devised various drying modes for large volumes of material, which were implemented in industry. In the revised Drying Theory, he surveyed a large amount of data derived from his theory on convective, radiation-convective, conductive, and freeze drying as well as drying in electromagnetic fields.

The monograph presents a rigorous exposition of the theoretical principles and deals with the heat and water transport mechanisms in open-pore bodies, which is used as basis for a detailed consideration of the coupled heat and mass transfer:

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

$$\frac{\partial T}{\partial \tau} = K_{21}\nabla^2 T + K_{21}\nabla^2 U.$$

These equations have been derived on the assumption that the heat and mass transfer coefficients and the thermodynamic characteristics are independent of the coordinates. It is also assumed that the water temperature in the capillaries is equal to the temperature of the capillary walls throughout the transfer, which is true only for diffusion-limited transport.

That system has been solved for many cases and various boundary conditions. It has been found that molar water transport is important, which is due to thermal and diffusion slip, and this has given a mass transport law for these porous bodies under nonisothermal conditions.

He used the general laws for heat and water transport in porous materials in a method of defining optimal and rational drying modes.

He thus presented the theoretical principles of coupled heat and mass transfer in porous bodies linked to the surrounding medium and established criteria and dimensionless quantities for them, which provided an up-to-date drying theory on the basis of his numerous and extensive researches.

He was one of the first to point out that Newton's law is not applicable to the specific heat flux q arising from a temperature difference ($T_W - T_\infty$) when the conditions at the surface are highly nonstationary (often very close to the actual situation):

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

and, therefore, one cannot use a heat-transfer coefficient α. He showed that the coordinates and time dependence of the wall temperature cannot be specified a priori and instead must be derived by solving together the equations for heat propagation in the liquid and solid together with the equations of motion, with the temperatures and heat fluxes equated at the solid—liquid boundary, i.e., one has a conjugate task in heat transfer. In that formulation, one incorporates the thermal interaction between the body and the liquid, which otherwise is independent of the properties of the medium and the body, the thermophysical characteristics, the dimensions, the source distribution in the body, etc., which is clearly physically unsound. It is particularly important to consider heat-transfer processes as linked in highly nonstationary processes. Even for very high thermal conductivities in the solid, the surface temperature cannot be taken as constant, since although it is independent of the coordinates, it varies in time. However, there is a difference from stationary heat transfer in that even in this limiting case the surface temperature as a function of time cannot be specified in advance, so virtually all cases of highly nonstationary convective heat transfer must be formulated as linked ones.

There are major mathematical difficulties in solving for linked heat transfer. One of them is that the equations are in partial derivatives and take various forms for the different regions, while in stationary treatments one even encounters differential equations of different types: for a liquid, one gets a parabolic-type partial differential equation, as against elliptic type for the solid. Lykov participated directly in developing new analytic and numerical methods and techniques for solving such cases. Nowadays, the conjugate formulation is generally accepted in science and engineering.

He also extended Prigogine's principle on the rate of change in entropy during transport and derived a new system of linear transport equations that differed from Onsager's system in that the fluxes are dependent not only on the thermodynamic driving forces but also on the rates of change and on the derivatives of the fluxes with respect to time.

That system implies transport equations that incorporate the finite substance propagation rates, which give hyperbolic differential equations for thermal conduction and diffusion as a particular case.

Heaviside operational calculus was widely used by him to solve nonstationary cases in thermal conduction theory.

A relationship was established between similarity theory (generalized-variable theory) and operational calculus, which gave the solutions a detailed physical meaning.

Boundary conditions of the fourth kind were introduced into the theory of thermal conduction. A rigorous formulation for convective heat transfer with the surface interacting with the environment was shown to correspond not to boundary conditions of the third kind, as had been generally assumed, but to ones of the fourth kind, so they acquired significance in convective heat transfer.

He also devised a new method of solving nonlinear problems in thermal conduction, where the thermophysical characteristics are dependent on the coordinates. That method gave some of the accepted methods of solving such problems as particular instances.

In more than 40 years of scientific activity, Lykov published about 250 papers and 18 books, including Drying Theory, Transport Phenomena in Open-Pore Materials, Thermal Conduction Theory, The Theory of Energy and Mass Transport, and Handbook on Heat and Mass Transfer. His books have been translated and published in Britain, France, Hungary, the US, and other countries. In 1951, he was awarded the State Prize First Class for his Drying Theory (1950), and in 1969 he was awarded the highest USSR distinction in heat engineering for his Theory of Thermal Conduction: the Polzunov Prize.

He had a highly developed sense of what is novel and an exceptional working capacity and self-discipline, which were qualities he also valued in colleagues and students. He attracted talented junior workers to the solution of complicated tasks and assisted in their creative growth and provided guidance on major parts of the work. He constantly recalled that a critical analysis of basic concepts in the theory is always useful and necessary, and that even an apparently strange idea should not be at once and categorically rejected, since only the availability of numerous new ideas generated by conceptual experiments can provide for successful developments in science and engineering. The Heat Physics Department he set up at the Lenin Belorussian University has trained highly qualified researchers in various areas of heat and mass transfer. Over a period of more than 40 years, he taught in technical colleges and directed the work of graduate students and colleagues. He trained 130 PhDs, 27 of whom went on to D.Sc.

His activities were particularly fruitful when he was director of the Power Institute, Belorussian Academy of Sciences, later called the Institute of Heat and Mass Transfer, which he headed in 1956. In a short period, which initially had only a small team of 30, this grew into a large heat physics center for the country. It eventually spawned the Nuclear Power Institute of the Belorussian Academy, the Water Problems Institute of the Ministry of Water of the USSR, and the Belorussian branch of the All-Union Krzhizhanovskii Power Institute.

In 1961, the Institute of Heat and Mass Transfer organized an All-Union conference on the subject. Since 1964, such conferences have been held every four years and have involved the participation of thousands of Soviet researchers and hundreds of foreign researchers. In 1969, the Institute was awarded the Order of the Red Banner of Labor for its great efforts in training scientific personnel.

His major contribution to heat physics received proper recognition. In 1956, he was elected Academician in the Belorussian Academy of Sciences and, in 1957, he was elected a member of the Academy of Building and Architecture of the USSR, and also in 1957 he received an award as an outstanding scientific and technical worker in the Russian Federation, also receiving the highest award in the country (the Order of Lenin) in 1967 and in 1970 the Order of the Red Banner of Labor.

He attached great importance to international scientific collaboration and strove to strengthen it. He took a direct part in organizing the International Journal of Heat and Mass Transfer in 1959, and in 1960 the Americal journal Heat Transfer: Soviet Research.

His activities were recognized in many countries. In 1969, he was elected a foreign member of the Mechanics Society of the Polish Academy of Sciences, and in 1971, his contribution to the science of heat and mass transfer was recognized by the government of Czechoslovakia, who awarded him a gold medal for services in the development of friendship and collaboration with Czechoslovakia, while in 1973 he was awarded the gold medal of the French Fuel and Power Institute.

He was also an organizer in the publication and the principal editor of this journal as well as a member of the editorial board of the Energiya publishing house and headed a committee on drying under the All-Union Scientific and Technical Society Council. Since 1959, he was editor of the International Journal of Heat and Mass Transfer.

He was not merely a well-known scientist, but also an active member of society. Twice, the people showed confidence in him in electing him to the Supreme Soviet of the Belorussian SSR, where he was a deputy from 1960 on. At the 26th Congress of the Communist Party of Belorussia, he was elected a member of the Revision Committee of the Central Committee, and at the next congress, he was elected candidate member of the Central Committee.

His outstanding talent, his deep understanding of science, and his confidence in and love of people, as well as his essential principles as a scientist, all together led to general recognition of Lykov as a social and political activist and one of the leading heat-science physicists.

His name has been commemorated in the name of the Institute of Heat and Mass Transfer of the Belorussian Academy, which was transformed by his efforts and those of his students into a widely known scientific center.