SOME CONCLUSIONS AND FORECASTS CONCERNING THE DEVELOPMENT OF THE SCIENCE OF HEAT AND MASS TRANSFER*

On December 30, 1972 the entire Soviet people will observe the 50th anniversary of the Union of Soviet Socialist Republics. This semicentennial is a great holiday for all our many nationalities.

The mere fact that the All-Union "Inzhenerno-Fizicheskii Zhurnal" published in Belorussian reports on some results of scientific progress all over the Soviet Union reflects one of the many instances of egalitarian development, indestructible friendship, and fraternal cooperation of all nations and nationalities in our country. In Belorussia — once a backward borderland of Tsarist Russia without either a research organization or any institution of higher learning prior to the establishment of Soviet rule — we have now many institutions of higher learning along with branches of the BSSR Academy of Sciences with a staff of over 7000, including over 800 Doctors and Candidates of Science. In various scientific fields the Institutes of the BSSR Academy of Sciences are recognized as leading posts of Soviet science.

A typical example is the Institute of Heat and Mass Transfer at the BSSR Academy of Sciences, which has been established with the assistance and fraternal cooperation of scientists from the Russian and other republics, where its highly qualified local staff is trained into a scientific pool and where scientists of many nationalities are working hand in hand — just as everywhere else in the Soviet Union. The institute is a leader in its field and is internationally recognized as such. Many foreign scientists come to the "Minsk" conferences on heat and mass transfer.

The Belorussian industry has grown, with the selfless fraternal help of other republics and the great Russian people foremost, and now provides a powerful base for scientific development in this republic.

Working shoulder to shoulder, we have built a communist society of peoples of over 100 nations and nationalities in the Soviet Union. And to whichever a Soviet man belongs, he takes foremost pride in being a citizen of the great Union of Soviet Socialist Republics.

The role of science in the USSR has expanded during the past few years as never before. Lenin's proposition that it is impossible to build communism without new scientific discoveries has been further elaborated in the historic resolutions of the 24th Communist Party Congress emphasizing the decisive importance of accelerating the scientific progress and the necessity of expanding the basic scientific research while fully utilizing the scientific as well as technical achievements and by all means reducing the timetable for the development and implementation of new technologies.

As is well known, an important role in new technologies is played by the science of heat and mass transfer — an unusually "interdisciplinary" science.

The science of heat and mass transfer is developing rather successfully at present and finds more applications in various branches of engineering. Here in the Soviet Union articles on heat and mass transfer are published in "Izvestiya Akademii Nauk SSSR Seriya Énergetika i Transport," in "Inzhenerno-Fizicheskii Zhurnal," in the journals "Teplofizika Vysokikh Temperatur," "Teoreticheskie Osnovy Khimicheskoi Tekhnologii," as well as in several others. Moreover, in 1959 the Pergamon Press (London/England) began to publish the "International Journal of Heat and Mass Transfer" with supplements.

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*This survey covers the last four years. A survey of the preceding four-year period was published in the "Inzhenerno-Fizicheskii Zhurnal" in 1967 (13, No. 5). This article is based on the report by A. V. Lykov to the Fourth All-Union Conference on Heat and Mass Transfer (Minsk in May 1972).

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We will discuss some problems and the various trends in the development of this science in the Soviet Union.

1. Transfer Theory

When analyzing the development of transfer theory, it is worthwhile to consider two trends separately: the phenomenological theory of transfer, and the microscopical or physical kinetics of transfer.

a. Phenomenological Theory. The transfer of a mass and of a heat pulse based on the interdependence of both represents the propagation of the respective quantity, in the form of integrodifferential equations. A further development in the phenomenological theory of transfer is accounting for the finite velocity of heat and mass flow, and a more general formulation of the problem for a variable continuum with the consideration of Riemann manifolds.

An important role in the development of transfer theory is played by thermodynamics of irreversible processes, where for the first time all transfer processes are seen continuously interlinked. In recent years this theory has been developed further still and the range of its applications continues to widen.

In connection with the development of rheophysics in such areas as rheodynamics, for instance, and especially in connection with the study of nonlinear transfer processes in complex systems, it became necessary to reexamine certain basic principles of irreversible-process thermodynamics as well as the Newton—Navier—Stokes, the Fourier—Kirchhoff, and the Fick laws of transfer. It has been shown in many thorough studies, for instance, that the classical transfer equations apply to a definite model of a complex continuum. Not all different materials and fluid media fit into this continuum model.

As a consequence, there has emerged a theory more general than the phenomenological one of irreversible-process thermodynamics and the classical hydrodynamic one of continuous-media thermomechanics. It is based on the laws of conservation (mass, momentum, moment of momentum, and energy). All different materials and fluid media are characterized by determining equations.

The general theory of thermodynamic determining equations is based on the principles of determinism, local activity, increase of entropy (the Clausius—Durem inequality), and simultaneity (a quantity appearing as an independent variable in one determining equation will appear in all equations, as long as its appearance does not violate the universal laws of physics or the conditions of invariability).

The four fundamental thermodynamic fields ($\mathcal{T}$, q, u, s) which depend on the history of deformation and temperature are described by the following functionals:

$$\left.\begin{matrix} \mathcal{T} \\ \mathbf{q} \\ u \\ s \end{matrix}\right\} = \left\{ \underset{\tau=0}{\overset{\infty}{\Phi}} [G(t-\tau),\ T(t-\tau),\ \dot{G}(t-\tau),\ \nabla T(t-\tau),\ \nabla\dot{T}(t-\tau)], \right. \qquad (1)$$

with $\mathcal{T}$ denoting the stress tensor, **q** denoting the thermal flux, **u** denoting the internal energy, **s** denoting the specific entropy, G denoting the deformation gradient, T denoting the temperature, and t, τ denoting time; a dot above a symbol denotes a derivative with respect to time.

The determining equations must satisfy the principle of mutually independent properties, the principle of simultaneity, and also the Clausius—Durem inequality:

$$\rho\dot{s} \geqslant \operatorname{div}\frac{\mathbf{q}}{T} + \dot{Q},$$

with ρ denoting the density and Q denoting the absorbed radiant flux (a dot above the symbol means that this is the derivative of flux with respect to time).

These determining equations and the principle of simultaneity do not contradict the laws of classical mechanics and of irreversible-process thermodynamics; from the determining equations (1) follows, as special cases, the equations of mechanics and the equations of thermodynamics.

For simple materials (fluids with linear viscosity and linear thermal conductivity, i.e., symmetrical systems) and for fluids for which the isotropy group of all four determining equations is a unimodular group we have classical and completely separable determining equations:

$$\mathcal{T}^D = \mu_1(\mathrm{tr}\mathcal{D})\vec{\vec{I}} + 2\mu\mathcal{D};\ \ \mathbf{q} = -k\nabla T,$$

$$u = F(s,\ v);\ T = \frac{\partial F(s,\ v)}{\partial s}, \tag{2}$$

with k, μ_1, and μ denoting respectively the thermal conductivity and the viscosity coefficient, $\mathcal{D}$ denoting the rate-of-deformation tensor, and v denoting the specific volume ($v = 1/\rho$). In deriving Eqs. (2) we have used a series expansion, assuming sufficiently smooth functionals Φ and applying the principle of a fading memory. Consequently, the classical separation of transfer effects follows for sufficiently symmetrical material sufficiently close to an equilibrium state.

Nonlinear thermomechanics of continuous media represents a further development in the phenomenological theory of transfer and, as special cases, it yields asymmetrical hydrodynamics, rheodynamics, and hyperbolic equations of heat and mass transfer.

As the criterion for the applicability of hyperbolic equations to describe heat and mass transfer serves the Veron number

$$\mathrm{Ve} = \frac{1}{R}\sqrt{\frac{(U_{\dot{T}})_e\, a}{c\rho}} \tag{3}$$

in the notation of nonlinear mechanics.

For processes with a finite rate of heat transfer w_q or with a finite velocity of the phase-transformation or chemical-conversion front w_f the Veron number is

$$\mathrm{Ve} = \frac{a}{w_q R} = \frac{a}{w_f R}. \tag{4}$$

Some scientists regard the new nonlinear thermomechanics of continuous media as a mere abstract science, but its fast development and successful application to the solution of practical problems completely defies this opinion. For instance, the principle of simultaneity has been confirmed in many experimental studies. Studies made at the Institute of Physics at the Latvian SSR Academy of Sciences have shown that the presence of magnetic fields adds new transfer coefficients which are tensor quantities and it produces transverse effects otherwise excluded according to the Curie principle of irreversible-process thermodynamics. It has been proven both theoretically and experimentally (Institute of Heat and Mass Transfer) that the heat transfer coefficient for a boundary layer in a stream of a plain Newtonian fluid around a solid body does, under certain conditions, become a tensor quantity which is a function of the velocity gradient in the fluid. The successful development of continuous-media thermomechanics not only defies the opinion of some scientists that all possibilities of the phenomenological theory of transfer have been exhausted, but also proves again how difficult it is to predict scientific developments.

b. Kinetics of Transfer Processes. The basic problem in developing a microscopical theory of transfer is to derive kinetic equations for cases other than the simplest ones (equations of the Boltzmann kind) and to completely formulate kinetic equations for condensating media. Significant progress has been made here during the last few years. A linear statistical and the fundamentals of a nonlinear statistical theory of transfer have been developed, along with a method of solving problems in transfer phenomena (Institute of Engineering Physics at the Ural Academy of Sciences), also a set of application problems has been solved (research done at the Central Boiler and Turbine Institute, concerning the condensation kinetics in supersonic streams through nozzles of various designs).

The methods of problem solving in physical kinetics have not yet been sufficiently refined, however. Solving the Boltzmann equation for the multidimensional case is rather difficult. The system of equations for the functions involved here is usually solved by breaking off the inifinite chain of equations at an appropriate point.

Progress in the solution of these problems is evidently tied in with an extensive use of the Monte Carlo method, its modifications, or similar methods.

Substantial progress has been made during the past few years in the development of statistical irreversible-process thermodynamics for systems with any degree of interaction. Thus, the basis is ready for constructing a general theory of irreversibility by the methods of statistical assemblies. These techniques, based on using Feinman diagrams and the nonequilibrium-statistics operator of correlational time functions, make it possible to analyze the nonequilibrium kinetics in systems with strong interaction.

Any problem in statistical equilibirum and nonequilibirum mechanics can be formulated in terms of an evolutionary kind of equation (e. g., the Liouville equation):

$$\frac{\partial \Phi}{\partial t} = L\Phi, \tag{5}$$

where L is a linear operator consisting of two parts:

$$L = L_0 + L_{\text{int}},$$

i.e., the evolution operator of free subsystems (particles or quasiparticles) L_0 and the operator of interaction between them L_{int}. This method can be applied to systems with strong interaction as, for instance, to solving problems of homogeneous turbulence.

It is to be noted that so far no single exact solution has been found to nonlinear kinetic equations. It is necessary to stimulate analytical and numerical studies of boundary-value problems in the kinetic theory of gases, which would be of considerable benefit to space engineering.

c. Analytical Research. Several interesting studies were published recently concerning the solution of boundary-value problems in heat conduction. Most attention has been paid to nonlinear problems, generalized methods of integral transformations, and to the solution of two- or three-dimensional transient problems (research done at the Polytechnic Institutes of Kalinin, Kuibyshev, Dushanbe, at the Leningrad Institute of Precision Mechanics and Optics, at the Belorussian University, et al.). Further developments have also been reported in the area of reverse heat-conduction problems (Riga Polytechnic Institute, Estonian Scientific-Research Institute, et.al.). New answers have been obtained to problems with moving boundaries (Moscow Pedagogical Institute, Latvian University, et al.). Large-scale research is continuing for the analytical solution of specific problems in heat transfer during laminar flow through pipes (monograph by P. V. Tsoi). Along with analytical methods are also successfully pursued approximate numerical solutions and methods of solving nonlinear heat and mass transfer problems by mathematical simulation on analog and digital computers (Institute of Applied Mathematics at the USSR Academy of Sciences). Solutions to nonlinear heat conduction problems have been analyzed both qualitatively and quantitatively (Institute of Engineering Thermophysics). The scope of analytical theory includes studies of asymptotic behavior and of stability, a study of higher-order perturbations, other qualitative studies, and, finally, discrete (important in computer techniques) as well as probabilistic simulation of equations.

II. Heat Transfer during the Flow of Liquids and Gases

a. Present State of the Art. So far solutions have been found to many heat transfer and hydrodynamic problems pertaining to laminar liquid and gas streams through channels of various shapes, at various boundary conditions, also with internal heat sources and dissociations. Significant results have been obtained in experimental studies concerning the hydrodynamics and the heat transfer where the properties of fluids are variable. Specifically:

1. Extensive experimental studies have been made concerning the heat transfer and the hydraulic drag in gas streams through stabilized pipe segments at gas temperatures within the 500-4700°K range and pipe wall temperatures within the 300-2000°K range (FTPÉ Institute).

2. A method has been developed for calculating the heat transfer and the friction at solid bodies in streams of dissociated and ionized air under pressures from 1 to 10 atm and at temperatures from 500 to 3000°K (Moscow Power Institute).

3. For the first time, the heat transfer in a nonequilibrium turbulent stream of N_2O_4 through pipes has been studied and a design method has been proposed which takes into account the kinetics of dissociation reactions (Institute of High Temperatures at the USSR Academy of Sciences, Institute of Nuclear Energy at the BSSR Academy of Sciences).

4. Experimental studies have been made concerning the heat transfer in carbon dioxide streams through pipes under supercritical pressure, with a Reynolds number $Re \approx (1\text{-}2)\cdot 10^6$, and with thermal fluxes up to $11 \cdot 10^6$ W/m^2, also with variable heat loads along the pipe. A strong effect of natural convection of the heat transfer has been discovered at high values of the Reynolds number, up to Re = 250,000 (Moscow Power Institute, Institute of High Temperatures at the USSR Academy of Sciences).

5. The effect of a density jump on the heat transfer has been studied along with the effectiveness of a gaseous suspension in a supersonic stream, also the effect of injection on the coefficient of recovery at a permeable surface within the gaseous suspension (Institute of Mechanics at the Moscow State University, Institute of High Temperatures at the USSR Academy of Sciences).

6. A complex of studies has been made concerning the heat transfer in channels of composite shapes with smooth or variously rough walls. An improvement of the heat transfer has been achieved by means of vortices generated by rotation and by detachment of the boundary layer (Central Boiler and Turbine Institute).

Much attention has been paid to the study of the turbulent boundary layer, because it plays a dominant role in many engineering areas. For instance, at the Siberian Branch of the USSR Academy of Sciences there has been developed a theory of the turbulent boundary layer where the viscosity decreases down to zero and a theory of quasilinear stability in an average-turbulent stream. Several fundamental laws governing the interaction between a turbulent stream and a solid body have been established without introduction of any empirical coefficients.

Correlational models have been designed at the Institute of Heat and Mass Transfer for a partial statistical description of momentum transfer processes and scalar sublimation, which do not contain any semi-empirical closing equations. An extensive series of experimental studies has dealt with composite correlation functions of velocity and temperature fluctuations under conditions of homogeneous anisotropy and heterogeneous turbulence (Institute of Heat and Mass Transfer).

A study cycle has been completed concerning the numerical solution of the equations of the turbulent boundary layer with a longitudinal pressure gradient (Leningrad University).

Although a large amount of experimental data is available and the hydrodynamics as well as the heat transfer in a turbulent stream have been studied extensively, the turbulence problem is by far not completely solved yet. For instance, no methods have been developed for calculating the turbulent boundary layer with mass transfer at the surface and a longitudinal pressure gradient in the mainstream.

Intensive progress is made in the physics of separation flow. It has been shown, for instance, that the Faulkner—Skan equation for a decelerating flow admits a solution with backcurrents.

Research dealing with heat transfer in free subsonic and supersonic jets as well as in jets interacting with solid barriers, with liquids, or with disperse media has been underway for a few years now at the Leningrad Institute of Mechanics. Several important results have been obtained, including a thorough understanding of the mechanism by which gas jets interact with liquid and disperse media.

The main concern of research for the immediate future in the field of heat and mass transfer during the flow of liquids and gases are: 1) heat and mass transfer in streams of gas mixture, considering the effects of chemical reactions as well as of gravitational, electrical, and magnetic fields; 2) transient heat and mass transfer processes, especially in pulse modes and in a strong radiation field.

b. Natural Convection. A considerable interest has developed in studies concerning the transfer processes under natural convection. In the Soviet Union research on this subject is well underway at the Perm University. Its recently published transactions contain a few interesting reports. Several studies were made recently concerning the natural convection in channels and orifices heated from above. It has been shown in studies at the Institute of Heat and Mass Transfer that small temperature, velocity, pressure, and density perturbations occur in a nonisothermal fluid with a constant temperature gradient. Most interesting are weakly attenuated thermal and transverse waves. Further developments in this direction have made it possible to discover photoabsorptive convection (convection occurring while the fluid absorbs passing light).

In the near future we will, obviously, continue to study convection in ferromagnetic and electrically conducting liquids.

c. Coupled Problems. An important step in the development of heat and mass transfer science is the new way of treating the convective transfer as a coupled problem (the temperature field of the boundary layer in a fluid is coupled to the temperature field of the solid wall). In this case, at the fluid—solid interface one formulates boundary conditions not of the third kind (Newton's law of convective heat transfer) but of the fourth kind (equal temperatures and equal thermal fluxes).

Such an approach was first proposed in 1961 in the Soviet Union and has now been accepted not only in this country but abroad as well. The validity of such a formulation has been confirmed both analytically and experimentally during the past few years, while the limitations of the conventional (old) approach have also been indicated.

It is possible to prove, by the methods of generalized variables (theory of similarity), that the criterion of coupling in problems of convective heat transfer is a quantity, the so-called Brun number, proportional to the ratio of two thermal resistances: that of the thermal boundary layer in the fluid and that of the solid wall. At values of the Brun number $\mathrm{Br} > 0.02$, within a 1% accuracy, a problem should be solved as a coupled problem. This Brun number is

$$\mathrm{Br} = \frac{\lambda_f}{\lambda_s} \cdot \frac{b}{x} \mathrm{Pr}^m \mathrm{Re}_x^n, \tag{6}$$

where λ_f and λ_s denote the thermal conductivity of the fluid and of the solid respectively, b denotes the plate thickness, x denotes the distance along the plate in the direction of the stream, Pr is the Prandtl number, Re_x is the local Reynolds number, and m, n are constants.

For laminar flow we have $m = 1/3$ and $n = 1/2$, for turbulent flow around a plate $n = 1/5$.

It follows from expression (6) that laminar flow is more affected by a solid wall than turbulent flow.

Under conditions of natural convection the Brun number becomes

$$\mathrm{Br} = \frac{\lambda_f}{\lambda_s} \cdot \frac{b}{x} \mathrm{Pr}^m \mathrm{Gr}_x^n, \tag{7}$$

where Gr_x is the local Grashof number within the range $10^2 < \mathrm{GrPr} < 2 \cdot 10^7$, and the constant $m = n = 1/4$.

Expressions (6) and (7) are valid when neither the fluid nor the plate contain heat sources. When there is a heat source in the plate, which is characterized by the Pomerantsev number Po, then the coupling criterion becomes $\mathrm{Br}^* = \mathrm{Br}/\mathrm{Po}$.

Over 100 articles were published during the last decade on the subject of coupled heat transfer problems.

d. Phase Transformations. Heat and mass transfer during boiling is an area of study of great interest as far as power applications are concerned.

It is to be pointed out that research in this area is underway at the Institute of High Temperature (USSR Academy of Sciences), at the Institute of Thermophysics (Siberian Branch of the USSR Academy of Sciences), and at other institutes. It was at these institutes where new modes of kinetic phenomena in liquid metals and nonmetals during boiling were first discovered and analyzed. A new method has been proposed for improving the heat transfer during boiling at fin surfaces, namely by depositing on these surfaces a thin coat of a material with low thermal conductivity, and adding small quantities of an inert gas. This has been proposed as a means of ensuring stable boiling of a liquid metal.

Large-scale research pertaining to heat and mass transfer during sublimation and desublimation is also in progress (Moscow Power Institute, Moscow Institute of Chemical Apparatus Design, Institute of Heat and Mass Transfer, et al.).

Important heat transfer and hydraulic studies have been made at the I. I. Polzunov Boiler and Turbine Institute concerning two-phase streams through pipes and channels.

III. Transfer Properties of Materials

As the most urgent areas in research concerning the transfer properties of liquids and gases must now be regarded experimental and theoretical studies of photonic heat conduction, of kinetic coefficients characterizing gases, gas mixtures, and metal vapors at high temperatures (above 1000°C), as well as the transfer properties of liquids at low temperatures.

The development of synthetic materials with prescribed properties represents one of the most significant aspects of technical progress. The scope of this achievement can be understood by merely considering that there are about 2.5 million different materials in existence and approximately 100,000 new formulations are being added every year.

The development of new technologies requires new structural and heat resistant materials which would remain stable at helium and hydrogen temperatures, under low vacuum for long periods of time, and when exposed to various forms of radiation.

An additional problem in studying the transfer properties of materials is created by the fact that the practical applications cover a rather wide temperature range: from liquid helium up to 3000-4000°C.

The basic trends in solid-state research over the next decade will be: 1) a composite study of physical properties over wide ranges of temperature, pressure, electric and magnetic field intensity, 2) a composite study of thermophysical properties of any structural materials based on refractory metals and alloys or on refractory compounds, 3) transfer properties of thin films and coatings.

Various analytical methods of estimating the properties of materials are already beginning to be used at present. A large amount of data has been accumulated within the last five years.

A scientometrical analysis of the development dynamics along this trend indicates an increase in research along separate microscopic and macroscopic domains with the use of model representations of the structure of matter.

The object of future analytical studies concerning the thermophysical properties of materials must be not only to predict the properties of existing materials but also to elaborate formulas for producing materials with prescribed properties.

An urgent task is to develop methods for a composite determination of transfer properties of materials: thermophysical, rheological, electrophysical, acoustic, hydro- and hydrometrical properties. For nonmetallic materials there are already known such methods for the composite determination of their thermo- and electrophysical properties. Within the next few years such a composite determination of physical properties will receive more and more attention.

IV. Fluidization System

Disperse systems with solid particles in motion and, particularly, fluidization systems are intensively studied in the Soviet Union and abroad. Such systems are much more complex than "classical" disperse systems with stationary particles but, accordingly, they have more and better controllable transfer properties.

From the rheological standpoint, fluidization sytems may exhibit properties of pseudoplastic and dilatant fluids, of a Bingham plastic, or of a Newtonian fluid.

The successful application of fluidization technology and, on the other hand, a few failures have recently stimulated a serious interest in the study of fundamental problems in fluidization hydrodynamics, in a search for and evaluation of methods of controlling the process as well as of predicting the "scale-up effect" (Moscow Institute of Chemical Apparatus Design, Institute of Heat and Mass Transfer at the BSSR Academy of Sciences, Institute of Catalysis at the Siberian Branch of the USSR Academy of Sciences). Several studies on this subject and dealing, more specifically, with "packed" beds have been completed and published.

For the purpose of attaining certain definite and prescribed properties other modifications of the fluidization process are being sucessfully developed: vibrofluidization, spouting fluidization, pulsed fluidization, and the electrothermal bed (Institute of Heat and Mass Transfer at the BSSR Academy of Sciences, Leningrad Polytechnic Institute, Moscow Institute of Chemical Apparatus Design, Institute of Physical Chemistry at the USSR Academy of Sciences, Gas Institute at the UkrSSR Academy of Sciences, et al.).

It is to be noted that a number of monographs on the subject of transfer processes and fluidization systems was published in this country during the last five years, including the books by Azarov and Todes, Baskakov, Zabrodskii, Makhorin and Tishchenko, Mukhlenov and associates, Romankov and Rashkovskaya, Romankov and Lepilin, Syromyatnikov and associates, and Chlenov and Mikhailov. These authors are scientists from various republics and cities of the Soviet Union.

During the same period we also published a few hundred original articles on fluidization problems.

V. Using of Capillary-Porous Materials in Modern Engineering

Studies concerning the heat and mass transfer in capillary-porous materials have become very urgent, owing to the use of porous heat exchangers (evaporators, condensers, sublimators), heat pipes, capillary pumps, sorption pumps, cryogenic condenser pumps, and cryogenic superconductors in various branches of engineering.

Most widely used are heat pipes. High-temperature heat pipes with sodium, lithium, lead, or indium as the heat carrier operate at temperatures from 600 to 2000°C. The transmitted power here reaches

2-10 kW/cm^2 levels. Low-temperature heat pipes operating at temperatures from −200 to + 230°C and using water, ammonia, alcohol, or liquid nitrogen as the heat carrier can transmit thermal fluxes ranging from 0.07 to 0.7 kW/cm^2 and can dissipate power ranging from 0.1 to 15 kW/cm^2.

Recently, in order to improve the performance characteristics of the capillary pump, heat pipes have been designed with channels through which the fluid can flow from condenser to evaporator along a path parallel to the main wick.

It is noteworthy that the diode characteristics of conical porous wicks and heat pipes with controllable thermal flux paths make it feasible to build switching devices and commutating systems. Heat pipes can serve as thermal flux transformers, diodes, triodes, and even thermal flux converters. The problem of neutralizing thermal stresses in diverse apparatus is being successfully solved with the aid of heat pipes.

Heat pipes are irreplaceable as thermal conduits for removing heat from atomic reactors, from anodes of thermionic-emission converters, from nozzles of plasma motors and fluid-reactor motors, also as means of thermostatizing the telescopes and other communication devices installed in satellites, etc. It is not by accident, therefore, that many articles have been published dealing with the physical mechanism by which liquids evaporate from model capillaries under normal pressures and under weightless conditions. Interesting studies on this subject are underway at the Institute of Physical Chemistry (USSR Academy of Sciences). Most of the experiments, however, are performed with single capillaries under isothermal conditions. Evaporation of a liquid from a capillary occurs always with temperature drops, both across the capillary wall and across the bulk liquid. Although these temperature drops are very small, they unfortunately have an appreciable effect on the capillary pressure within the range of high air saturation. For this reason, any conclusions from such experiments must be drawn with a great deal of caution.

Scientific-engineering programs have been followed in recent years pertaining to electric power transmission over cryogenic lines. Preliminary calculations show that cryogenic transmission lines become preferable to conventional cables for power blocks larger than 1000 MW and preferable to conventional overheat lines for power blocks larger than 5000 MW.

The cooling of superconductors and cryogenic conductors can be improved appreciably by the use of capillary porous materials for such conductors. With a current conductor constructed in the form of an elastic porous matrix, it can be cooled by filter and capillary flow of the cryogenic liquid through the pores with attendant phase transformations.

VI. Aerothermoptics

Aerothermoptics is an excellent example illustrating the significant role which heat and mass transfer theory plays in scientific and technical progress. The development of aerothermoptics is a consequence of our life standard, namely of the need to increase the quantity of information transmitted over communication channels (telegraph-telephone, television, and radio channels). The perfection of laser techniques has made it possible to use optics as communications. The basic advantages of optical over radio-frequency and superhigh-frequency systems are the much higher volume (by approximately six orders of magnitude) of transmitted information and the use of noiseproof wideband transmission components. The high directivity of such a transmission system allows an appreciable reduction in the transmitter power. The simplest version is an open system, i.e., communication over the air. A few experimental open lines are operating in the USSR and abroad. Atmospheric conditions are very variable (rain, fog, snow, dust, etc.), however, and the energy losses are high. Atmospheric turbulence, sunlight, starlight, moonlight, and terrestrial light sources produce noise. All this causes an open system to become unstable and, in some cases, unfeasible. For this reason, more attention is now paid to the development of closed communication lines. Such systems must contain focusing devices which naturally compensate for the divergence of light beams as well as for random and intentional bending of the optics. Optics can operate with discrete dielectric mirrors, glass lenses, and glass fibers. One of the interesting and promising trends is the development of thermoaerodynamic optics, where convective gaseous lenses are used as corrective elements.

The principle of the simplest thermoaerodynamic optics is that, as a laser beam travels inside a plain tube in a nonuniform temperature field, the light beam deflects in a predetermined direction. Lenses are made of hot gas with specific temperature drops.

The science of aerothermoptics, which has thus evolved at the interface of classical optics with heat and mass transfer theory, aims at attaining required properties of a medium by means of thermal, aerodynamic, and concentration effects; optical methods of determining the transfer properties of substances are also of concern here. One important area of aerothermoptics, where it actually started as a new science, is the development of optical wideband communication lines (optics). This branch of modern technology continues developing at a fast rate.

It may be concluded from this brief analysis that the new branch of science dealing with heat and mass transfer is passing through a period of rapid growth, merging into a variety of general modern trends in science and engineering. Technical progress in heat and mass transfer depends largely on prior developments in power as well as by the development and synthesis of new materials and processes. Among these governing aspects of technical progress, the science of heat and mass transfer forms one of the bases on which new technologies are built.