SOME RESULTS IN HEAT- AND MASS-TRANSFER DEVELOPMENT

> "Only under Socialist conditions does the scientific and engineering revolution discover its true direction to respond to the interests of humanity and society. Likewise, only by accelerated development of science and technology can the ultimate tasks of the Socialist revolution be solved, and a Communist society be constructed."*

One of the most important scientific facets of contemporary science, heat and mass transfer, is a complex of scientific information, constituting an independent scientific discipline. It combines the hydrodynamics of continuous media, thermodynamics, thermophysics, molecular physics of disperse systems and chemical kinetics. Heat and mass transfer is an important practical matter in solving problems in the production and use of energy, in other words, in the power industry, in the technical processes of the chemical, light engineering and food industries, and also in the production of building materials. Questions of heat and mass transfer are particularly important in helium production and in water distillation, in the atomic power industry, and in laser production of materials and rocket technology, as well as in a number of other areas of modern technology.

A large contribution to the development of the science of heat and mass transfer has been made by A. V. Lykov, Academician of the Academy of Sciences of the Belorussian SSR (AN BSSR), who was Director of the A. V. Lykov Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR (ITMO AN BSSR) in the period 1956-1974.

Some results of investigations conducted by the leading institutes of the USSR in the field of heat and mass transfer in recent years are described below.†

GENERAL HEAT- AND MASS-TRANSFER THEORY

Phenomenological Theory. In the area of phenomenological theory there has been further development in methods of solving coupled convective heat-transfer problems. It is well known that A. V. Lykov and T. L. Perel'man have shown that, generally speaking, one cannot give the wall temperature a priori, as a function of the coordinates and the time, but must determine it by simultaneous solution of the equations of heat propagation in the solid and the liquid, along with the equations of motion. This approach is particularly important when one studies intense unsteady thermal processes, for which the basic characteristics depend both on the liquid properties, and the properties of the immersed solid. At ITMO AN BSSR an asymptotic method has been developed for solving nonlinear singular integrodifferential equations, to which many problems in heat-transfer theory can be reduced. This technique has been applied, in particular, to solve coupled problems, and also to solve the boundary-layer equations in the presence of a chemical reaction of order n at the body surface. At the F. É. Dzerzhinskii All-Union Heat-Engineering Institute (VTI), widely based investigations have been conducted into coupled unsteady heat transfer in channels of different shapes under both laminar and turbulent flow conditions. The small parameter method has been widely used to find an approximate solution of nonlinear boundary problems in heat and mass transfer (including coupled problems) [ITMO AN BSSR, Institute of Technical Thermophysics of the Academy of Sciences of the Ukrainian SSR, (ITTF AN UkrSSR)].

Perturbation methods (employing asymptotic expansions) are being used in heat-conduction theory. By introducing a certain small parameter (e.g., a relatively small extension of the body in one measurement) into

*Papers of the Twenty-Fifth Congress of the CPSU [in Russian], Politizdat, Moscow (1976), p. 47.
†A paper on this topic was published in the November issue of Inzhenerno-Fizicheskii Zhurnal in 1967. Therefore, information given there is not repeated here.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 33, No. 5, pp. 773-801, November, 1977.

0022-0841/77/3305-1265$07.50 ©1978 Plenum Publishing Corporation

the conditions of the problem, one can use the procedures of singular perturbations, widely used in liquid and gas mechanics, and thereby, in particular, one can account for effects associated with the differences between actual problems and one-dimensional models [the Leningrad Polytechnic Institute (LPI) and the Kuibyshev Polytechnic Institute (KuPI)].

At present, methods have been developed and continue to be improved for reducing heat-transfer experimental data, based on solution of the inverse heat-conduction problem (determining boundaries of thermal regimes and heat-transfer coefficients from knowledge of the temperatures within a body). It is well known that inverse problems are invalid according to the Adamar criterion, and that one must use special methods to solve them in order to obtain results which are both stable and sufficiently accurate (e.g., the Tikhonov regularization method, the quasitransformation method, etc.). In addition to the coupled heat-transfer problems, we can use the inverse boundary-problem approach to investigate the complex processes involved in unsteady thermal interaction of solids with a surrounding medium. Significant results in solving improperly posed problems in the reduction of experimental data have been obtained at Moscow State University (MGU), Moscow Aviation Institute (MAI), and other scientific establishments.

Recently practical requirements have generated a considerable volume of work aimed at calculating temperature fields in bodies of complex shape and in systems of bodies. In particular, at the Leningrad Institute for Precision Mechanics and Optics (LITMO) methods have been developed for calculating thermal conditions and thermoelastic stress fields in instruments, and these can be regarded as a system of many bodies with heat sources and external energy processes, varying in a different manner in space and time. The mathematical model of these processes is a system of many equations in partial derivatives, interconnected by mixed boundary conditions. Methods widely applied to calculate temperature fields in bodies of complex shape include the following: the structure method, based on the application of the Ritz variational method, where the body geometry is given in analytical form by means of R-functions; the finite-element method; reduction of an original three-dimensional heat-transfer problem in bodies with cooling channels to a series of two-dimensional problems, which are then solved by variational methods; the simultaneous use of the Laplace transform and the Galerkin method [the Khar'kov Polytechnic Institute (KhPI), the Institute for Mechanical-Engineering Problems of the Academy of Sciences of the Ukrainian SSR (IP Mash AN UkrSSR), N. É. Bauman Moscow Higher Technical School (MVTU), ITMO AN BSSR, the Tadzhik Polytechnic Institute (TadPI)].

A prominent place in contemporary heat-transfer theory is occupied by problems in heat conduction with moving boundaries. The methods for solving these problems differ appreciably from the classical methods of mathematical physics. Here one must differentiate between problems where the boundary motion is given, e.g., (filtration theory, soil mechanics and the mechanics of oil strata), and problems where the motion must be determined from supplementary conditions given at the unknown phase-transition boundary (Stefan problems). Of the analytical methods presently applied, one should mention the method (for problems with a given law of boundary motion), using a special transformation, of reducing the original problem in a region with moving boundaries to a moving coordinate system where one can apply classical methods, and also the series method, which is suitable for a broad class of problems, including computation of crystallization and sublimation processes [the Physicotechnical Institute of the Academy of Sciences of the USSR (FTI AN SSSR), the V. I. Lenin Moscow State Pedagogical Institute (MGPI), and the I. P. Bardin Central Scientific-Research Institute of Ferrous Metallurgy (TsNIIChermet)]. In the development of new methods for processing materials by means of concentrated energy fluxes (lasers and electron beams) a problem arises in determining the speed of the solid–gas interface. In the electron-beam case a volumetric heat source can form in the specimen and cause phase transitions even inside the solid. Specific details of this kind in a process, along with the one-dimensional nature of the problem, considerably complicate the investigation [the Institute of Metallurgy of the Academy of Sciences of the USSR (IMet AN SSSR), the Institute of Theoretical Physics of the Academy of Sciences of the USSR (ITF AN SSSR), ITMO AN BSSR].

The search continues for methods of solving equations of coupled heat and mass transfer in capillary-porous and porous media, describing the more complex physical models for these processes: the flow of phase transitions over a temperature range, the calculation of migration of moisture toward a phase-transition front under Stefan boundary conditions, calculations for multilayer media, calculation of phase-transition kinetics in individual capillaries, etc. [MGU, the Kalinin Polytechnic Institute (KaPI), ITMO AN BSSR, etc.].

In the convective heat-transfer area there is great interest in solving closed equations for turbulent shear flows under different pressure-gradient conditions for the axisymmetric nonisothermal wake with given excess momentum [the Institute of Physicotechnical Power-Engineering Problems of the Academy of the Lithuanian SSR (IFTÉ PAN LitSSR), ITMO AN BSSR], and in the development of the theory of quasilaminar stability of the wall region of a turbulent boundary layer [the Institute of Thermophysics of the Siberian Branch of the Academy of Sciences of the USSR (ITF SO AN SSSR)]. Far-reaching theoretical investigations in heat transfer in high-temperature gas flows, under conditions of suction and blowing of a liquid through porous channel walls for both laminar and turbulent flow conditions, are being carried out at the Institute of High Temperatures of the Academy of Sciences of the USSR (IVT AN SSSR), the G. M. Krzhizhanovskyi Power-Engineering Institute (ÉNIN). In radiative heat-transfer theory methods are being developed for calculating anisotropic scattering [the D. I. Mendeleev All-Union Scientific-Research Institute of Metrology (VNIIM) and the Moscow Polygraphy Institute (MPoI)], for calculating heat transfer in furnace facilities [the I. I. Polzunov Central Scientific-Research, Planning and Design Boiler and Turbine Institute (TskTI) and ÉNIN], and also for calculating radiative heat transfer in molecular vibrational and rotational bands [the Institute of Physics of the Academy of Sciences of the USSR (IF AN SSSR)].

Among the theoretical results (ITF SO SSSR) one should note the following: the development of a hydrodynamic theory for critical boiling; the creation of a gravitational model for transformation of single-phase convection of a metastable liquid to developed film boiling; the theory of a boundary layer with vanishing viscosity; the asymptotic theory of the thermal curtain; the creation of a generalized correlation model for electric-arc plasma generators; the theory of waves in liquid with gas bubbles and on the surface of liquid films; and the elementary theory of a boiling layer of solid particles.

At ITMO AN BSSR a theory is being developed for nonlinear thermomechanics of memory materials. The simplest form of memory is recognition of a finite rate of propagation of an appropriate Maxwell stress. The known models of a ferromagnetic liquid have been generalized in order to take more fully into account their physical properties, particularly the finite anisotropy, and the hydromagnetism of ferromagnetic particles suspended in a liquid. Investigations are continuing, aimed at creating methods of accurate, approximate and numerical solution of heat- and mass-transfer problems with free and forced convection in rheologically complex liquids.

Among the numerous investigations of recent years in the area of numerical methods for calculating heat- and mass-transfer processes one should note the development of numerical methods: for nonlinear problems in heat conduction and radiative magnetohydrodynamics [the Institute of the Problems of Mechanics of the Academy of Sciences of the USSR (IPM AN SSSR)]; for problems in heat and mass transfer with phase transformations [MGU, ITTF AN SSSR, Computation Center of the Latvian State University (VTs Latv GU), the E. O. Paton Electric Welding Institute of the Academy of Sciences of the Ukrainian SSR (TÉS AN UkrSSR), S. M. Kirov Tomsk Polytechnic Institute (TPI)]; in the theory of heat transfer with free convection (IPM AN SSSR, ITMO AN BSSR, etc.); for contact problems in heat conduction in multilayer media and structures [MAI and the Voronezh State University (VGU)]. There has been further development in methods for solving the heat-conduction equations by electric modeling [ITTF AN SSSR, KhPI, the Tula Polytechnic Institute (TuPI)].

Kinetic Theory. Along with the development of phenomenological heat- and mass-transfer theory there has been substantial development in investigations in the area of physical kinetics. These investigations are necessary, in particular, for correct formulation of boundary problems in heat and mass transfer, and for determining the limits of application of the various phenomenological relations. In the area of heat transfer in porous materials, studies include the following: the kinetics of evaporation and condensation in capillaries of finite length for various degrees of rarefaction of gas flow; and mass transfer in model capillary systems, allowing for surface phenomena [ITMO AN BSSR and the Institute of Physical Chemistry of the Academy of Sciences of the USSR (IFKh AN SSSR)].

At present the study of heat- and mass-transfer processes in different branches of science and engineering leads to investigation of boundary problems in the kinetic theory of gases and gaseous mixtures. The solution of these problems makes it possible to analyze various nonequilibrium processes: the dynamics of gas flow with internal degrees of freedom and chemical reactions [N. E. Zhukovskii Central Institute of Aerohydrodynamics (TsAGI), A. A. Zhdanov Leningrad State University (LGU), "Énergiya" (nongovernmental organization), Moscow Engineering-Physics Institute (MIFI), Moscow Institute of Physics and Technology (MFTI)]; the kinetics of evaporation and removal of material in vacuum [Computation Center of the Academy of Sciences of the USSR (VTs AN SSSR), the Institute of Physics and Technology of the USSR Academy of Sceiences (IFT AN SSSR), ITF SO AN SSSR]; interaction of gas molecules with surfaces [LGU, VTs AN SSSR, and the Ural Polytechnic Institute (UPI); gas flow with temperature and concentration gradients, for which the ordinary gasdynamic equations are not suitable [TsAGI, Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Academy of Sciences of the USSR (ITPM SO AN SSSR)]; formation of a new phase in a supersaturated vapor, and the kinetics of transfer phenomena in disperse media and other chemical engineering processes (IPM AN SSSR).

Kinetic theory methods are also used to calculate transfer coefficients in gaseous mixtures (MGU, ÉNIN, ITMO AN BSSR). In particular, at ÉNIN methods have been developed and programs written for computer calculation of coefficients of viscosity, heat conduction, diffusion, and thermodiffusion of chemically reacting gaseous systems and alkali metal vapors. These programs have been used to calculate the above transport properties of combustion products of organic and special fuels, and also of alkali metal vapors, over a wide range of temperature and pressure variation.

II. CONVECTIVE HEAT AND MASS TRANSFER

Forced Convection Heat Transfer. At IVT AN SSSR a theory has been developed for the convective heat-transfer process in a Newtonian liquid and gas with variable properties, and a wide range of experimental investigations has been made into different aspects of this topic. The result has been the creation of methods of computing heat transfer and flow resistance under intense heat-flux conditions in flows of monatomic, diatomic, and polyatomic gases and liquids under high temperature differences and at high speeds, in flow of heat-transfer agents under near critical conditions, and in flow of liquid and gases in a gravitational mass force field.

Theoretical and experimental investigations have been made into the hydrodynamics and convective heat transfer of liquid metals. As a result, methods have been developed for calculating heat transfer and flow resistance in flow of liquid metals in tubes with internal heat sources, for motion of liquid metals in a magnetic field, and for boiling of a liquid metal in tubes and in a large vessel.

In recent years systematic investigations have been made into heat-transfer processes in dissociating systems, and a study has been made of the interaction of turbulent transfer and chemical transformations. This study has generated methods for calculating heat transfer in equilibrium and nonequilibrium flows of a dissociating gas in tubes, heat release and critical heat fluxes in boiling of a dissociating heat-transfer agent, and heat transfer during condensation of a dissociating vapor.

The results of the investigations performed are being used in engineering design of high-flux heat-exchange systems in the power industry and other branches of engineering. These have found a prominent place in the design of nuclear reactors, steam generators and other facilities of atomic electric-power plants and thermal electric-power plants.

At ITF SO AN SSSR investigations in convective heat transfer are in progress, linked to problems of wall turbulence, critical and wave processes in gas-liquid systems, the mechanics of a liquid during phase transformations, and the dynamics and energy transfer in flow of a rarefied gas and a gas-discharge plasma.

Of the theoretical results of ITF SO AN SSSR the development of heat-transfer theory in the turbulent boundary layer with vanishingly small viscosity, the theory of quasilaminar stability of the wall region of a turbulent boundary layer, the asymptotic theory of heat screens, and the theory of waves in a liquid with gas bubbles and on the surface of liquid films are noteworthy.

Among the significant experimental results in the convective heat-transfer field one can identify the discovery of the retarding effect and the long "memory" of a retarded boundary layer on a permeable surface, the strain effect in components of the turbulent stress tensor under the influence of high-polymer molecules, singular waves on the surface of free-flowing liquid films, the multiextremal nature of the velocity profiles in gas–liquid flows, the inversion of the rotational degrees of freedom when a gas expands in vacuum, and the cluster-formation effect.

The original techniques developed at ITF SO AN SSSR for optical, electrochemical, and electron-beam diagnostics of gas–liquid and mixed flows have enabled detailed investigation of certain characteristics of wall turbulence, the structure of a boundary layer in a supersonic gas flow, the presence of pressure gradients, nonisothermal effects, transverse mass flux, and chemical reactions at the walls in conditions with strong inertia forces and interaction with various external fields.

At ITMO AN BSSR a number of statistical models has been developed for turbulent transfer of momentum and heat. A differential description has been proposed for inhomogeneous velocity and temperature fields in a third-order approximation, where all the single-point moments of the fields of velocity, temperature and pressure are determined by appropriate differential equations. This third-order approximation model differs in principle in these features from the well-known earlier second-order models, in which the third moments are modeled by means of approximate relations.

In recent years a treatment has been developed for turbulent theory, based on using an equation for the finite-dimensional probability distribution function. A closed Fokker – Planck type equation has been obtained for the simultaneous two-point characteristic function, containing all the two-point statistical information on the turbulent temperature and velocity fields. An approximate solution of this equation leads to closed equations for the structural velocity and temperature functions.

There has been considerable interest in solving turbulent transfer problems using the well-known moment models. Programs have been developed for numerical computation of equations of parabolic type for wall and free nonisothermal turbulent shear flows, which allow one to calculate averaged characteristics for velocity, temperature, components of the Reynolds stress tensor, heat-flux fluctuations, rate of dissipation of kinetic energy, and rate of dissipation of the temperature field.

Study of cavitational flows has generated a number of new facilities for vacuum technology, for constant environment studies, and for technological processes associated with dispersion and homogenization of several phases.

A large amount of work has been done in studying heat- and mass-transfer processes with interaction of capillary-porous bodies and a gas stream in the presence of phase and chemical transformations. The study includes the heat- and mass-transfer process occurring with thermal resonance waves, when the displacement rate of a heat source is determined by the mass transfer in porous systems as they are traversed by gas mixtures. The results of these investigations have been used to develop and commission various absorption and catalytic facilities, used, in particular, to purify gaseous emissions.

The investigation of heat and mass transfer in slotted channels with chemical and phase transformations present, accounting for the effects of free convection, thermal diffusion, and diffusion conduction, has made it possible to construct a number of reactors for chemical deposition of semiconductor and dielectric thin films, which are used successfully in electronics factories.

An engineering method has been devised for calculating the multicomponent reacting boundary layer, allowing for chemical reactions inside the immersed bodies and the breakdown (combustion) of material from the body surface, and making it possible to compute the distribution of Schmidt and Prandtl numbers, the concentration and temperature in the reacting boundary layer, and the variation in the position of the reaction zone and the thermophysical coefficients as a function of the intensity of blowing or suction of injectant.

The investigations into heat- and mass-transfer processes in hydrogen – oxygen fuel elements, accounting for the capacity of the system for self-regulation, have made it possible to develop a number of guidelines for optimizing such procedures, and promoting the construction of actual specimens of these generators in the USSR and abroad.

Significant results have been obtained in the field of aerothermal optics. Gaseous analogs have been developed and fabricated for solid-body optical elements: gaseous lenses (or focusing elements) of various types, refracting devices (or prisms and wedges), and aerodynamic windows (or plane-parallel plates).

Some agreement has been found between thermal and hydrodynamic parameters, when the optical power of a thermal gas lens is practically independent of Reynolds number or of the flow rate. This is a very valuable operational property of gas lenses and allows some fluctuation in gas flow rate without affecting the optical characteristics of the lens.

A large set of investigations into the transmission of laser radiation to great distance have been performed. Thermal gas lenses have been used in thermohydrodynamic light guides as focusing elements which compensate for the ray divergence, and also for random or intentional curvature of the light-guide axis. Numerical modeling has determined relationships between the thermohydrodynamic light-guide parameters, to secure minimum loss in the transmitted radiation. A test facility has been built for modeling the propagation of radiation in actual light guides, and has been used for a set of investigations to determine the optimal optical characteristics of thermal gas lenses.

Semiempirical methods have been developed at ITTF AN SSSR for investigating the inverse transition of a turbulent flow to laminar, and an effective method has been proposed for calculating thermal-transition processes. Programs have been written for numerical calculation of the laminar flow of a compressible gas in tubes and channels with heat transfer, including allowance for variable thermophysical properties of the medium. Methods have been developed for solving coupled liquid gas flow problems. Methods have been investigated for intensifying convective heat transfer, and from these efficient heat-exchange surfaces have been determined, and technology and equipment to produce these have been developed at IÉS AN UkrSSR. The basic data have been developed for a number of areas of heat-transfer theory: in single-phase media, in turbulent and fluctuating flow, in systems of jets interacting with an obstacle, in permeable metallic materials, and in closed cavities filled with liquid. The IÉS AN UkrSSR engineers have collaborated with a number of leading turbine and automobile factories to create and bring into practical use optimized systems for air cooling of the majority of steady-state gas turbine equipment, a number of large-capacity road and aviation gas turbine engines, and also for the internal-combustion engine.

The IFTÉP AN LitSSR has made a detailed study of heat transfer in conditions of external liquid flow over various surfaces as a function of the liquid properties at Prandtl numbers from 0.7 to 10^4, the effect of roughness of an immersed surface and the degree of turbulence of the external flow have been investigated, and a set of experimental studies has been made of heat transfer in a high-temperature boundary layer, for laminar, transition and turbulent flow conditions. In addition, investigations have been made to study heat transfer in the nonequilibrium state of a high-temperature flow of combustion products from a propane – oxygen mixture: the heat-transfer laws have been identified for thermal dissociation of a gas in flow in channels, around cylinders, and in tube bundles.

In recent years ITFÉP AN LitSSR has carried out a number of applied investigations, defined by questions in the atomic energy field.

At TsKTI heat transfer under longitudinal flow conditions has been investigated with various liquid-metal heat-transfer agents at Prandtl numbers from 0.007 to 0.03 in bundles of rods with various relative pitch and rod (or tube) location relative to the lattice of an equilateral triangle ($s/d = 1.05$-1.5) under conditions $q = \text{const}$. Data has been obtained on the surface temperature distribution of a tube bundle. For relative pitch of $s/d =$ 1.1, 1.2 and 1.5 theoretical heat-transfer coefficients have also been determined. From the results of these investigations the average heat transfer has been calculated in tube (or rod) bundles located at the vertices of an equilateral triangle ($s/d = 1.1$-1.5) for laminar ($30 \leq Pe \leq 200$) and turbulent ($200 \leq Pe < 2000$) flow conditions with pure metals.

An experimental investigation of heat transfer in transverse flow has been made in various tube bundles of chessboard and corridor arrangement over a wide range of variation in the relative pitch, and in the Prandtl number range 0.03-0.007. Average values of heat-transfer coefficients in the range $50 < Pe < 7000$ and $0.007 < Pr < 0.03$ have been obtained, with variations in local heat-transfer coefficient over the perimeter of tubes located in different rows inside the bundle.

At VTI in recent years a broad range of investigations has been conducted in convective heat transfer in the power circuits of thermal and atomic power stations.

Experimental papers have been published on heat transfer in turbulent tube flow of air, nitrogen dioxide, and argon at Reynolds numbers of $(25$-$500) \cdot 10^3$, at wall temperatures from 300 to 3000°K, and temperature ratios from 1.02 to 3.2. A correlation of the experimental data has yielded empirical formulas for calculating Nusselt number or explicit tube wall temperature, for a substantial variation in the thermophysical properties of the different gases, over a wide range of conditions.

Widely ranging investigations have been completed to elucidate the laws for convective heat transfer in tubes, annular channels, and rod bundles with variable heat load on the wall along the channel and variable thermophysical properties of the heat-transfer agent.

Data have been obtained on unsteady heat transfer in tubes and channels, and also for heat transfer in tubes where the state parameters of the heat-transfer agent are supercritical.

At ÉNIN there has been a theoretical and an experimental study of heat transfer at supercritical pressures with a number of organic and cryogenic liquids.

For organic liquids the basic heat-transfer laws have been established experimentally, as well as the causes for intensification of heat transfer under conditions of pseudoboiling and thermoacoustic self-oscillation.

A theoretical investigation has been made of the influence of mechanical energy dissipation and variation in flow physical properties on the heat transfer in cryogenic liquids, and recommendations have been made for the design of elements of power-generating facilities.

A solution has been found for heat transfer in conditions where liquid is blown in and drawn out through porous walls of circular and two-dimensional channels with both laminar and turbulent motion of liquids similar to the blown liquid.

Heat Transfer in a Mass-Force Field. For a long time, free convection has been considered as a factor which had not much effect on convective heat transfer. There has been a renewal of interest in heat transfer in a gravitational field (or an equivalent inertial force field), due to the new scientific and technical applications, and also to the possibilities which are opening up with development of numerical methods.

In the book by Gershun and Zhukhovitskii "Convective Stability of an Incompressible Liquid" (1972) numerous investigations of convective stability in laboratory conditions have been correlated, where the effect of compressibility of the medium is minor and may be neglected. The influence of various factors on stability has been analyzed: a magnetic field, rotation, nonuniformity of composition, modulation of the parameters, internal heat sources, capillary effects, etc.

Systematic numerical investigations of thermoconvective processes in a compressible gas have been carried out at IPM AN SSSR.

Much work has been done at ITMO AN BSSR to investigate convective heat transfer in closed volumes where there is nonuniform heat transfer over the heat-transfer surface, and photoabsorptive convection, where electromagnetic radiation is absorbed by the liquid. These and other new problems in natural convection have been examined in a monograph by Lykov and Berkovskii (1947). Local heat transfer in cavities has also been studied at LITMO.

Another new area of work carried out at ITMO AN BSSR is the study of wave processes in the transfer of heat and momentum in unstable stratified media. Detailed numerical and physical experiments have been used to clarify the mechanism for propagation and to obtain new characteristics for these waves called thermoconvective waves.

Certain features of natural convection in rheologically complex media have been examined at ITMO AN BSSR, where a number of boundary problems involving convective heat transfer with nonlinear-viscous liquids have been examined in the boundary-layer approximation.

In the Chemical Physics Branch of the Institute of the Academy of Sciences of the USSR in Chernogolovk (OIKhF AN SSSR) the influence of natural convection has been investigated in chemically reacting systems, where gradients of temperature and concentration occur during chemical reactions of the substance, causing convective motion.

At ITF SO AN SSSR a detailed investigation has been made of the structure of thermal gravitational flows near heat-transfer surfaces. The laws have been discovered for flow and heat transfer in turbulent natural convection.

A mass-force field may be electromagnetic in nature. Then the heat-transfer processes in a gravitational field, in polarizing and nonmagnetic media, will be defined as thermogravitational forces, like the electrodynamic action of external electromagnetic fields. The influence of electrical fields on convective heat transfer in dielectric liquids has been investigated at the Institute of Applied Physics of the Academy of Sciences of the Moldavian SSR (IPF AN MoldSSR).

The production and the widespread study of the properties of magnetic liquids possessing powerful magnetic properties have led to the possibility of controlling flow and heat-transfer processes by external magnetic fields. At ITMO AN BSSR a study has been made of the laws of heat transfer in magnetic liquids under themal convective conditions. Intensive investigations of convective heat transfer in magnetic liquids have also been conducted at the Institute of Physics of the Academy of Sciences of the Latvian SSR (IF AN LatvSSR).

There is great interest in studying heat transfer under the simultaneous action of forced and free convection. At IVT AN SSSR a wide program of work has been accomplished on flow and heat transfer in tubes under conditions where thermogravitational forces have an appreciable effect. The range of variation of Reynolds number extends from viscous to turbulent flow conditions. A review of work on mixed convection is included in the monograph by Martynenko and Sokovishin (1975).

Interaction of High-Temperature Gas Flows with Various Materials. In the last decade there has been a sharp increase in the number of scientific publications on interaction of high-speed and high-temperature gas flow with surfaces of different materials, and it is therefore possible to mention only the most major work dealing with analysis of new topics or reviewing the many results of theoretical and experimental investigations.

The main directions of contemporary investigation of physical and mathematical aspects of coupled high-temperature gas flows with materials can be classified as follows: 1) physicochemical processes on the disintegrating surface of a body washed by a gas stream; 2) heat and mass transfer within a high-temperature coating, in general a composite coating; 3) thermophysical properties and their dependence on temperature and heating conditions.

We should first mention the books by Dushin "Studies of Heat-Shield Materials in High-Temperature Gas Flow" (1968) and by Polezhaev and Yurevich "Heat Shielding" (1976), which are the first attempts in a monograph to describe contemporary approaches to the basic question of coupled high-temperature gas flows and disintegrating heat-shield materials. In these books the numerous surface physical and chemical transformations are divided into several types, depending on the breakdown mechanism, basic concepts are given as to the kinetics and thermal effects of surface and volume processes involved in decomposition and transformation of condensible substances in a multicomponent boundary layer, and equations are given for flow of the molten layer under the action of pressure gradient and friction in the oncoming flow. In the second book a large section deals with investigation of the behavior of heat-shield materials under combined convective–radiative thermal action, and a review is given of the basic methods and equipment for experimental investigation. The monograph by Pankratov et al. "Interaction of Materials with Gas Flows" (1976), describes features of the behavior of semitransparent materials under the action of convective and radiative heat flux, and also gives details of interaction of a surface with a two-phase stream.

Among the theoretical investigations dealing with surface physicochemical transformations, one should mention the work of Russian scientists published in the collection "Heat Transfer, 1974, Soviet Investigations" (1976).

Among the experimental investigations on this topic one should mention the work of Yakushin and Georg "Thermal boundary layer on models disintegrating in a high-enthalpy gas stream" (Mekh. Zhidk. Gaza, No. 1, 1976), which contains very valuable results of measurements of temperature profiles and concentrations in the boundary layer on the disintegrating surface of a composition material.

There has been strong activity in recent years in investigating heat and mass transfer inside high-temperature coatings continuing the classical work of A. V. Lykov and detailed, in particular, in the books "Theory of Heat Conduction" (2nd. ed., 1967), and "Theory of Drying" (2nd ed., 1976). These have widespread practical application, and the general methodology and some results can be seen in the monographs "Basic Heat Transfer in Aviation and Space Technology" (1975), "Basic Practical Theory of Combustion" (1973), in the book by M. P. Kuz'min "Electrical Modeling of Unsteady Heat-Transfer Processes" (1974) and also in the monograph mentioned above by B. M. Pankartov et al. There is interest in a booklet by O. F. Shlenskii "Thermal Properties of Plexiglas" (1973), where topics in thermal transparency state are considered, along with nonequilibrium heat- and mass-transfer processes inside composite coatings.

Unsteady heating of heat-shield coatings is associated with simultaneous flow of chemical reactions, thermal breakdown of the organic component, filtering of gaseous products through the porous subsurface layer, removal of the nonorganic component mass along with the gas washing the external surface, and also with a large temperature drop, resulting in major variations of all the thermophysical properties. Numerous journal articles have dealt with these topics.

The present armor-coating materials are in essence systems with a memory. Their behavior and their properties are determined not only by the temperature distribution, but also by the heating prehistory. Since one can calculate thermophysical properties of multicomponent decomposing materials until limits are exceeded, it is important to systematize and analyze the experimental data. In this regard one should note the monograph by A. G. Shashkov and V. I. Tyukaev "Thermophysical Properties of Decomposing Materials at High Temperatures" (1975), and also the work of O. F. Shlenskii.

The development of contemporary technology steadily increases the requirements for accurate determination of various physical and mechanical properties, especially the thermal conductivity. In recent years many papers in this direction have appeared, dealing both with methods of calculating these properties, and also methods for experimental investigation. Examples are the monograph by G. N. Dul'nev and Yu. P. Zarichnyak "Thermoconductivity of Mixtures and Composite Materials" (1974), and also the book by E. S. Platunov "Thermophysical Measurements under Monotonic Conditions" (1973). There have been great developments in methods of solving linear and nonlinear inverse heat-conduction problems used to determine the thermophysical properties of materials.

III. HEAT AND MASS TRANSFER WITH PHASE TRANSFORMATIONS

Heat transfer and hydrodynamics of the flow of liquids and vapor with phase transformations (boiling, evaporation, condensation and sublimation) find wide use in a number of technical areas. Investigation of this process has been the subject of a number of ongoing scientific and research institutes in the USSR.

At VTI experiments have been conducted to investigate the hydraulic resistance in flow of nonequilibrium and equilibrium water–vapor mixtures in tubes and annular channels with equilibrium and nonequilibrium heat-flux distribution along the channel over a wide range of pressure and heat flux. A technique has been developed for calculating conditions for the onset of surface boiling and for transition from nonequilibrium to equilibrium two-phase flow. The heat-transfer crisis has been investigated for boiling of a liquid in channels. The nature of the boiling crisis has been elucidated. At present work is being done to investigate the local characteristics of water vapor flow using optical holography.

A program of work has been carried out to study the process of condensation of a pure vapor with impurity of noncondensing gases in tubes.

At TsKTI heat transfer and hydraulic flow are being investigated under conditions with external flow over stepped systems of power equipment elements. The experimental investigations of boiling of water in a large volume under conditions with developed bubble boiling in the pressure range 1-200 kg/cm^2 have yielded a reliable design formula for determining the heat-transfer coefficient. A single empirical design relationship has been obtained for determining the heat-transfer coefficient in boiling of water in tubes for various levels of pressure, heat flux, and flow speed. This empirical formula allows one to calculate heat transfer in any zone along the channel of a vapor generator from the single-phase flow region to the region of dispersed-annular flow.

Investigations have been conducted into heat transfer with condensation of water vapor inside vertical tubes and channels of different geometry, and a single correlation equation has been obtained.

At ÉNIN investigations are continuing into heat transfer and hydrodynamics of liquid metals, especially potassium boiling under forced motion in straight tubes and honeycombs. Methods have been developed for thermal and hydraulic design of vapor generators heated by a liquid metal. A program of work has been carried out to use aluminum as the high-temperature heat-transfer agent.

An analysis has been made of flow features with two-phase media (air–water, water–vapor, and potassium–vapor) in nozzles and at nozzle exits.

The flow of two-phase vapor–liquid streams has been investigated in the mixing chamber of an injector-condenser, allowing for interaction of the drops with the flow. Radiation methods have been developed for investigating the hydrodynamics of two-phase media, and a program of investigations has been carried out into the steam-generation process in thermal and atomic power stations. The laws have been established for flow of two-phase flows in the steam-generating elements of steam boilers and atomic power reactors.

A theoretical and experimental investigation has been made of heat transfer at supercritical pressure with a number of organic and cryogenic liquids. The influence of mechanical energy dissipation and variation in the physical properties of the flow on the heat transfer in cryogenic liquids has been investigated theoretically.

At ITF SO AN SSSR unique equipment has been built to investigate heat transfer with boiling and condensation. Among the theoretical results published by ITF SO AN SSSR one should note the development of a hydrodynamic theory for the boiling crisis and the creation of a cavitation model for transition in one-phase convection of a metastable liquid into developed film boiling, and among the experimental results one should note the work on visual study of the boiling process in liquid metals, and investigation of heat transfer in boiling, condensation and bubbling of a wide class of heat-transfer agents. The ITF SO AN SSSR has had considerable success in introducing scientific developments into industry. For example, a good deal of work has been devoted to tests on a Freon turbine in geothermal sources, and so on.

At ITMO AN BSSR work has been done to investigate heat transfer with boiling and condensation of low-boiling-point (water, ammonia, acetone, alcohols, Freons, etc.) and cryogenic heat-transfer agents on developed and porous surface of power-engineering equipment elements (heat pipes, steam chambers, etc.).

Theoretical investigations have been conducted into the process of boiling of a liquid inside porous bodies with filtration motion of the heat-transfer agent and volume generation of heat, or with a heat flux supplied to a surface. Different forms have been devised for low-temperature and cryogenic heat pipes (coaxial, centrifugal, with screwed inserts, with a noncondensible gas present, etc.) and test rigs to investigate the phase-transition process during filtering of cryogenic liquids along porous channels, and heat pipes with volumetric heat sources.

Major and broadly based investigations of the heat- and mass-transfer process with phase transitions, have also been conducted at a number of the leading scientific-research institutes in the USSR (IVT AN SSSR, ITTF AN UkrSSR, etc.).

IV. RADIATIVE HEAT TRANSFER AND COMPLEX HEAT AND MASS TRANSFER

One promising direction for development in high-temperature technology involves processes in a low-temperature plasma. With these one can appreciably intensify many chemical and metallurgical processes and can also develop new methods for producing materials and improving production quality and quantity. In the present decade there have been far-reaching scientific investigations, which have accumulated information required for the development of plasma engineering processes, studies have been made of phicochemical, and optical transition properties of a low-temperature plasma, the theoretical foundations have been developed for plasma chemistry, and the possibility of accomplishing various plasma processes has been investigated.

At IVT AN SSSR a theory has been developed for a nonequilibrium plasma where for the first time the plasma is considered as a single system of interconnected components. Analytical expressions have been obtained relating the internal plasma parameters to the external conditions. This has opened up possibilities for computing the thermophysical and electrical characteristics of a plasma under steady and unsteady conditions, describing the development of ionization, the de-ionization rate, and so on. A general approach to the problem has yielded a number of approximate engineering formulas, as well as criteria giving the boundaries of application of the various simplifications used in the literature.

The results of these developments have found application in calculations of the state and properties of a plasma in closed-cycle MHD generators, thermoelectric converters, plasma motors, high-power gas lasers, and other plasma energy facilities. These are also used in electrical-breakdown theory, in plasma chemistry, and in describing some photochemical processes.

At ITF SO AN SSSR and ITMO AN BSSR a generalized correlation model has been developed for low-temperature plasma electric-arc generators.

The results of investigations of heat and mass transfer and of gasdynamics of a low-temperature plasma have been generalized in monographs and in selections of papers ["The Physics and Technology of the Low-Temperature Plasma" edited by S. V. Dresvin (1972); "Heat Transfer in an Electric-Arc Gas Heater" by A. G. Shashkov et al. (1974); "Applied Dynamics of a Hot Plasma" by M. F. Zhukov et al. (1975); and a series of three collections of papers edited by M. F. Zhukov published in 1974 by the Siberian Branch, Nauka (publisher): "The Theory of the Electric Arc in Forced Heat-Transfer Conditions," "Experimental Investigations of Plasmatrons," "Properties of the Low-Temperature Plasma and Diagnostic Methods," etc.].

Some of the ministries and departments [the Ministry of Industrial Chemistry of the USSR (Minkhimprom SSSR), the Ministry of Nonferrous Metallurgy of the USSR (Mintsvetmet SSSR), et al.] are approaching practical success in plasma technological processes. Test facilities and industrial experimental units have been set up. A number of processes have been introduced and used successfully in production (different methods for plasma treatment of surfaces and powders, plasma fusion, etc.).

In the last decade important investigations into heat- and mass-transfer processes in the furnaces of steam generators have been conducted at TsKTI.

The primary radiation characteristics were determined for the first time for the basic types of solid fuels used in the power industry in the Soviet Union. From these data a method was developed for calculating the emissivity of a coal-dust flame, accounting for the relative contribution to the total flame radiation of particles of coal-dust, ash and coke, and also of the triatomic gases (H_2O and CO_2), formed by an actual industrial burner in the furnace chambers of steam generators.

A method has also been developed for calculating the thermal radiation of a flame when there is compression of petroleum residue and gas, and this reflects the influence on radiative energy transfer of the radiative properties of CO_2 and H_2O and particles of carbon soot formed during compression of the fuel. The calculations account for the degree of filling of the furnace volume by the luminous part of the flame.

Spectra have been obtained for the radiation of coal-dust and petroleum-residue flames in an actual burner under industrial conditions, illustrating the features of the selective nature of the thermal radiation. These show substantial selectivity of the petroleum-residue flame in comparison with the coal-dust flame. The results of these investigations are being used to improve methods of calculating heat transfer in steam generator furnaces.

Work has been done to produce a technique for calculating local and total heat transfer in steam-generator furnaces. Coefficients for the thermal efficiency of screens typical for the various fuels have been determined.

It was shown for the first time that the anomalously low values of the thermal conductivity of the layer of external deposits on the screening tubes contributes a high thermal radiation flux into the furnace volume, reaching up to 50-60% of the incident radiative flux. This new discovery explains the comparatively low thermal efficiency of screens in steam-generator furnaces.

The results of theoretical and experimental investigations have formed the basis of a new normalized method for heat calculations of boiler assemblies, devised by TsKTI in conjunction with VTI in 1973, and this is a major achievement of the two groups of scientists in the 1950's. At present this paper is used in the design of steam generators in all the boiler construction factories in the USSR. It has also been widely used abroad, in the countries of the Socialist group. This indicates the importance of the results obtained in the USSR of scientific investigations into heat and mass transfer in the furnaces of boiler assemblies. The experimental data give a good confirmation of the new design technique.

At ÉNIN, in addition to the development of heat-transfer calculations for the furnace chambers of power-industry boilers, a solution has been found to the complex problem of molecular-radiation heat transfer in vacuum systems with perforated screens, using a diffuse-specular surface reflection model. A method has been proposed for investigating complex heat transfer in gas flow over a plate with a first section whose temperature varies with time according to a given law. New radiometric instruments have been produced to measure the radiative properties of solid materials and radiative fluxes of various levels, and a series of new techniques has been developed for experimental investigation of the radiative properties; the instruments and the techniques can be used to obtain radiative property data for the range of materials used in technology.

Methods have been suggested for measuring the fields of temperature, velocity and heat flux in high-temperature gas jets. The Gretz problem has been solved, including radiative transfer.

At ITTF AN UkrSSR theoretical and experimental investigations have been conducted into unsteady thermal processes in steam and gas turbines. Nonlinear methods have been developed for analysis and calculation of process dynamics in combustion chambers, heat exchangers, and turbocompressor assemblies. An analysis has been made of the thermal state of turbine rotors during start-up, and the allowable conditions of thermal stress have been determined for the operating conditions of gas turbine equipment.

At ITF SO AN SSR tests have been made of a Freon turbine in geothermal sources, development has been completed and investigations conducted of fan equipment for the power, chemical and agricultural industry, and so on.

V. HEAT AND MASS TRANSFER IN FLUIDIZED SYSTEMS

In recent years in the Soviet Union successful development has continued of basic and applied investigations of fluidized systems.

It is well known that investigations of heat and mass transfer in fluidized beds constitutes an independent facet in the science of heat and mass transfer, both in the Soviet Union and abroad. This is to be expected, since most solids are subjected to heat and chemical processing, and exist in a coarsely dispersed state. In addition, dispersed materials are highly efficient intermediate heat-transfer agents. Fluidized systems are a promising and the most complex form of coarsely dispersed gas – solid systems (or liquid – solid systems) with moving particles, much more complex, but richer in study topics and applications than simple systems with fixed particles and filtration media, which have been thoroughly studied for many decades.

In recent years in the USSR more than 20 original monographs have been published on different heat-transfer topics in the fluidized bed. These include that by Gel'perin et al. on the basic technology of fluidizaation (1967), by Syromyatnikov et al. on interphase heat transfer in the fluidized bed (1967), that by Alekseev and Astaf'ev on the baking of nickel concentrates in a fluidized bed (1967), that by Chlenov and Mikhaiov on drying in a vibration-boiling layer (1976), that by Aerov and Todes on the hydrodynamic and thermal foundations of operation of equipment with steady and boiling layers (1968), that by Syromyatnikov and Rubtsov on thermal processes in ovens with a fluidized layer (1968), that by Romankov and Rashkovskii on drying in a fluidized layer (1968), that by Baskakov on heating and cooling of metals in a fluidized bed (1968 and 1974), that by Koganovich and Elobinskii on industrial equipment for drying in a fluidized bed (1970), that by Mukhlenov et al. on catalysis in a fluidized layer (1971) and in a foaming layer (1975), that by Zabrodskii on the general question of developing high-temperature equipment with a fluidized bed (1971), that by Dement'ev on thermal calculations of multizone ovens with a fluidized layer (1971), that by Razumov on fluidization and pneumotransportation of friable materials (1972), that by Chlenov and Mikhailov on the properties and use of a vibrofluidized layer (1972), that by Kazakova on the granulation and cooling in equipment with a fluidized bed (1973), that by Borodul on high-temperature processes in an electrothermal fluidized bed (1973), that by Todes et al. on dehydration of solutions in a fluidized bed (1973), that by Tishchenko and Khvostukhin on design of ovens and heat exchangers with a fluidized bed (1973), that by Borodul and Gupalo on mathematical models of chemical reactors with a fluidized bed (1976), and that by Rabinovich on thermal processes in a fountain bed (1977).

Investigations of fluidized systems have been conducted to improve our understanding of the specific influence of the hydrodynamic structure of the beds on the heat and mass transfer occurring there, the technical realization and the economics of industrial operation of technical processes.

The appropriate theoretical work has been performed in different areas, not only concurrently, but also independently. Some are associated with a statistical description of the system, and others with attempts to represent fluidized systems as especially deterministic, in the hope of linking the experimental investigations to the analytical ones, and, in particular, to construct a picture of the solid phase motion from the measured local gas velocity field. Various approaches have been followed in mathematical modeling of fluidized systems in order to obtain numerical relationships for the design of engineering equipment with a fluidized bed and to calculate the scaling factors.

In some work the bed is described microscopically as a single entity possessing specific characteristics for transporting the gas and the solid phase. In other less conventional forms of two-phase models ("bubble models") attempts have been made to calculate (and describe) the actual structure of nonuniform fluidized systems with the birth, growth, and gaseous transfer of bubbles from the emulsion "phase."

Scientists at IPM AN SSSR have solved the problem of an exact derivation and completeness of the universal transport equations in heterogeneous disperse media. In parallel with this, at ITMO AN BSSR there was proposed and developed an alternate transport model, a convenient one in that the balance equations include a single kinetic coefficient besides the known thermophysical properties of the dispersed medium. This coefficient determines the intensity of relaxation heat transfer at the gas interface and the properties of a universal constant over a wide range of change of the disperse medium properties. If we exclude from consideration the appreciably unsteady part of the heat-transfer process, then the transport theory can simplify the closed equations, and, as a result, both approaches lead to identical equations for the heat balance.

The ideas that have been developed lead to a universal relationship in the Nu, Fo coordinate plane, forming a good correlation of the test data, and so one can calculate or estimate the convective heat-transfer intensity at the interface with the dispersed bed.

In regard to the hydrodynamics and the modeling of fluidized systems one must note the work accomplished at IPM AN SSSR, the Institute of Catalysis of the Siberian Branch of the Academy of Sciences of the SSSR (IK SO AN SSSR), the Moscow Institute of Chemical Engineering (MIKhM), the Tambov Institute of Chemical Engineering (TIKhM), the Institutes of the Ministry of the Chemical and Oil-Processing Industries, (IMKh-NeftProm), and the Ural Polytechnic Institute (UPI).

There has been a great interest in recent years in carrying out investigations of the propagation of gas jets in a fluidized bed. A topic of fundamental importance is the study of the development of jets in bed nonuniformities such as gas bubbles. The major applied topics here are associated with the calculation of gas-distribution equipment, control of gasdynamics of thin fluidized beds, etc. Important investigations into jets have been conducted at MIKhM and TIKhM, and at IPM AN SSSR.

Theoretical and experimental investigations have been conducted (at ITMO AN BSSR) into unsteady heat transfer between a surface and a layer of dispersed material at small Fourier number, allowing for the difference in the speed of propagation of the thermal wave in the solid and gaseous phases. These are important for our understanding of the special features of heat transfer in a fluidized bed and the surface in contact with it, in regard to the predictions of the well-known bunch model.

In place of the excessively simplified representation of the "practical isotherms" of fluidized systems it has become recognized that one must systematically study the actual nonisothermal features, both macroscopic and microscopic (in terms of the spatial coordinates, not the temperature differences). We must do this both to discover ways to increase the operational efficiency and reliability of equipment with fluidized beds, and also to understand some of the basic laws of heat transfer in fluidized systems, particularly the role of radiative transfer, especially heat transfer at low fluidization numbers and in beds with fittings.

Because of the need to calculate nonisothermal aspects, it has become very important to study thermal diffusivity of fluidized systems, particularly of "organized" (or stagnated) systems.

A number of groups have worked on the hitherto almost uninvestigated matter of heat transfer of gas jets with fluidized beds. Heat transfer has been studied for beds fluidized under vacuum and at pressures over atmospheric; heat transfer in beds fluidized by liquid drops; heat transfer in vibroboiling and fountain beds and in some new modifications of fluidized systems.

Significant results have been obtained at ITMO AN BSSR on these and other heat-transfer topics, at the Institute of Gases of the Academy of Sciences of the Ukrainian SSR (IG AN Ukr SSR at UPI, at MIKhM and TIKhM, the Moscow Institute of Small Scale Chemical Technology (MITKhT) ToPI, the State Institute for the Nitrogen Industry (GIAP), and at ITTF AN UkrSSR.

Prompted by the increasing interest in recent years in conducting high-temperature processes (1000°C and more) in a fluidized bed, heat-transfer investigations have been conducted in electrothermal fluidized systems and in boiling layers with heating of gas and liquid fuels [ITMO AN BSSR, UPI, IG AN UkrSSR, TsKTI, and the Institute of Oil Technology and Heat Synthesis of the Academy of Sciences of the USSR (INTS AN SSSR)].

Boiling-bed ovens have been developed for nonoxidizing heating of metal and for other purposes [ITMO AN BSSR, UPI, IG AN UkrSSR, the State Scientific-Research Institute of Machinery for the Building Materials Industry (NIIStrommash), the Donets State Scientific-Research Institute of Ferrous Metallurgy (DonNIIChERMET).

Boiling beds in the temperature range 900-1000°C have proved to be promising for solving the problem, both present and future, of an economical and ecologically "clean" heating of inexpensive solid fuels. Experimental and theoretical investigations in this area have been begun at ITMO AN BSSR, UPI, and TsKTI.

It is well known that even the ordinary bed fluidized by a gas has a wide range of control of transportation properties (e.g., the heat-transfer coefficients and thermal diffusivities). The possibilities of creating dispersed systems with assigned properties have expanded greatly with the use of various modifications of the fluidized bed: beds with fittings, vibroboiling, pulsed beds, three-phase beds, fountain beds, etc.

In the last decade in the Soviet Union a vast amount of information has accumulated on the hydrodynamics and the transfer properties of a number of modifications of fluidized systems and some new modifications have been proposed. Of these we may select a fluidized bed and the fountain bed, in which the medium fluidized or caused to exhibit fountain behavior is not a gas but a gas-suspension (ITMO AN BSSR and UPI), and also a vibrorotation bed, where the fluidization is created by rotation of the stepped floor of the equipment (ITMO AN BSSR),

In the course of investigations into the fountain bed, ways have been proposed for overcoming the defects formerly considered to be inherent in this kind of system, i.e., the "low precision", the poor use of high-temperature gas heat-transfer agent, and the unsuitability for processing finely dispersed material.

"Strip" fountain beds have been suggested, multistep opposing beds with expanded entry of gas and with pulsed blowing (ITMO AN BSSR).

VI. HEAT AND MASS TRANSFER IN DRYING PROCESSES

In the last decade work has continued, aimed at further development of the theory of drying, a broad study of transfer processes in high-intensity drying of various classes of material, combined with the development of new methods of dehydrating them with different forms of energy input, and also the principles for controlling these processes, to optimize them and to obtain high-quality products and materials with given properties.

A program of investigations conducted at ITMO AN BSSR is aimed at a broad study of the functional relationships between the variation of the volumetric average temperature of materials and their average mass content with the energy supplied convectively. Methods have been suggested for calculating drying processes, based on the Rebinder number. New microbiological materials have been investigated as drying objects (their hydroscopic thermophysical and physicochemical properties). A new method has been developed and introduced for drying these materials in the form of solutions and suspensions in swirling intersecting jets under active hydrodynamic conditions.

High-intensity methods have been proposed and introduced for combined thermal and radiative drying of different types of polymer coatings on substrates. In many cases these allow the hardening processes to be accelerated by an order of magnitude, yielding sealing or technological materials with the required properties. Engineering and precision methods have been devised for designing heat-radiation thermal drying facilities.

Improvement in the recirculating method of drying grain products has continued, aimed at more fully conserving the quality of seed grain and increasing its penetration energy. An important feature are investigations to develop methods of drying grain products which would eliminate the occurrence of carcinogenic compounds.

A method has been developed for drying chemical and pharmaceutical preparations. This is based on theoretical investigations of heat- and mass-transfer processes in two-phase flow with a solid phase modeling the type of preparation investigated.

Thermophysical principles have been developed for high-temperature vacuum drying of capillary-porous materials, based on an example of multilayer cellulose, subjected to thermal-oxidation destruction.

A program of theoretical and experimental development has been carried out to investigate heat and mass transfer in disperse systems with discrete energy supply, for various hydrodynamic conditions, allowing for the specific features of the process, e.g., for oscillatory conditions.

The results of a study of the laws of transfer processes under vacuum conditions with sublimation of various substances and flow of the sublimate in slotted channels have been implemented in new high-intensity heat- and mass-transfer equipment, which is being used in various branches of the new technology.

From the multifaceted experimental and theoretical investigations which have been carried out industrial types of aggregates and mechanized systems have been developed and introduced into industry for high-intensity drying of medical preparations, and swirling and crushing machinery for dehydration of various liquids and suspensions, as well as automatic equipment for drying polymer and compound coatings on manufactured articles, and so on.

At ITTF AN UkrSSR a theory has been developed for heat and mass transfer in gas – liquid polydispersed systems, a theory has been developed for the dispersion of jets and a method has been found for monodispersion of melts and solutions, a two-stage atomizing plant has been built for evaporation and drying of heat-sensitive biological and chemical solutions which are used in the food and medicinal industries. Wide use is made of a method of high-temperature drying by a moist heat-transfer agent for accelerated drying of bricks, plaster boards, engineering materials, etc.. Methods have been developed at ITTF AN UkrSSR for thermal plasticizing and oxidation-stabilizing of cellulose in a vented moving bed, for high-temperature drying of moving thread, and accelerated processes for forming various items has allowed appreciable improvement in the production technology for chemical, artificial and natural fibers.

At the Moscow Technical Institute of the Food Industry (MTIPP), proceeding on the hypothesis that the product of the initial drying rate by the time it reaches a given ambient moisture content is constant during the drying process, for a given moisture content (independent of the conditions), laws have been developed for the kinetics of moisture removal. The laws found have enabled methods to be developed for generalizing the kinetics of heating and drying and universal relations and reliable approximate methods have been developed for calculating the drying kinetics, including the duration. This has made it possible to model the drying process and to bring drying theory into line with practice.

An accurate two-zone calculation has been proposed for the drying process, where the second stage is divided into two parts with their own drying factors.

An analysis of the kinetics of the moisture-removal process and the development of test data based on generalized curves are now used by many organizations and technicians engaged in drying, and from this one can proceed from a single test to numerical results for a great many cases pertaining to different conditions, without performing additional experiments.

With the methods which have been developed and vigorously implemented for analysis and calculation of drying of moist materials, together with the basic integral equation of kinetics, one can determine all the basic characteristics of the process (the moisture content, the drying rate, the duration of drying, the heat-transfer intensity, the average temperature, etc.).

Investigations have been conducted on introducing liquid products directly into a vacuum-sublimation chamber, and also on sublimation drying during vibration transportation, and this makes it possible to build improved direct-action sublimation equipment.

Equipment has been developed and built to investigate the electrophysical properties, in particular, of food materials of different moisture content in single-mode and multimode superhigh-frequency fields, and a study has been made of the degree of nonuniformity in the energy distribution of an electromagnetic field in the working volume of resonant-cathode systems. The possible use of superhigh frequency for drying a number of food products and sterilizing liquid materials in a flow has been examined.

At MTIPP and ITMO AN BSSR methods have been developed and a spectral apparatus has been built for studying the optical properties of various radiation-scattering materials; a theory has been developed for energy transfer by thermal radiation in capillary-porous colloidal substances and other selectively absorbent and scattering materials; methods have been improved for calculating heat and mass transfer, accounting for absorption of infrared radiation passing through the material, and numerical values have been found for the heat-radiation characteristics of many moist products and materials; and a technique has been developed and design nomograms have been constructed for designing the working chambers of thermal-radiation equipment and for estimating their operating efficiency.

At the Lensovet Leningrad Technological Institute (LTI) numerous methods have been developed for drying materials in a boiling bed. This pertains to drying of solutions and pastes in a boiling bed of inert coarse-grained heat-transfer agent and drying of moist disperse material in equipment with slots for supplying gas. The slotted equipment, which has layers with asymmetric fountain-type or swirling motions, is distinguished by its high efficiency and simple construction. The region for stable fluidization conditions has been determined (without formation of channels and pistons), and its dependence on the equipment geometry.

The equipment and technical processes introduced for drying and heating have allowed substantial enhancement of the heat- and mass-transfer processes in many fields of industry and automatic assembly lines to be built, and they have increased productivity and simultaneously improved the production quality.

VII. HEAT AND MASS TRANSFER IN RHEOLOGICALLY COMPLEX SYSTEMS

The sharp recent growth in the interest exhibited by investigators and engineers in flow and heat transfer in rheologically complex media and its intensive development in the USSR and abroad are a natural response to urgent practical requirements. The majority of Soviet publications, mainly articles and reports, is devoted to the rheodynamics and steady heat transfer under laminar flow of nonlinearly viscous liquids (non-Newtonian, the so-called "power-law fluids") in tubes and channels, relating to processes of polymer development. In fact, in practice, particularly in heat and energy technology, one meets much more frequently with nonlinearly viscoplastic media, which begin to flow after overcoming some initial limiting shear stress (e.g., peat; highly viscous and impregnated liquid-disperse materials; water–coal suspensions; slurries; fuel mixtures and compositions; paste-like and other fuel materials with polymer bonding; greases; pastes and suspensions of nuclear fuel; petroleum residues, etc.). The mechanical behavior of these flowing media and the nature of the heat- and mass-transfer processes in them differ to an extreme degree, depending on the individual and special materials, and one cannot ignore this.

The problem of heat and mass transfer in rheologically complex flowing media began to be investigated first in the sixties [the Azerbaidzhan Institute of Oil and Chemistry (AINKh), the Kazan' Technological Institute (KazTI)]. However, substantial progress in formulating theoretical, experimental, and applied investigations of the transfer processes in rheologically complex media was reported after the All-Union Symposium on Heat and Mass Transfer in Non-Newtonian Liquids, held in Minsk, March, 1966. Due to the initiative of Academicians A. V. Lykov and P. A. Rebinder, active scientific-research activity began at ITMO AN BSSR in the rheophysics area.

At the Third (1968), Fourth (1972), and Fifth (1976) All-Union Conferences on Heat and Mass Transfer at Minsk, there were special rheophysical sections and the proceedings were published in three volumes. In 1969, at ITMO AN BSSR, the All-Union Conference on Physical and Chemical Engineering was held and two volumes of papers were published on theoretical and applied rheology. In 1970 an International Seminar on Heat Transfer in Rheological Complex Media was held in Yugoslavia. At the Fourth International Conference on Heat Transfer (Paris, 1970) there was an independent section on heat transfer in rheological complex liquids for the first time. In addition, several issues of the "Inzhenerno-Fizicheskii Zhurnal" were fully devoted to rheophysics subjects. Progress in the development of the problem was reported at the Eighth All-Union Symposium on Rheology (Gomel', 1974) and at the First International School on Heat and Mass Transfer in Rheologically Complex Liquids (Minsk, 1975). A significant contribution toward solution of this problem was made by workers at ITF SO AN SSSR. Using a new rheological model for a structurally viscous liquid, S. S. Kutateladze and E. M. Khabakhpasheva solved the problem of rheodynamics and heat transfer in circular and two-dimensional channels for classes of exponential and linear-law fluidity. These theoretical developments were added to careful experiments in which improved techniques and equipment for stroboscopic examination of the motion of microstructural elements was used. Subsequently, the investigations were concentrated mainly on the study of the turbulent structure of wall flow when polymer additives were introduced into the flow. Simultaneously, special features of transfer processes in viscoelastic concentrated polymer solutions were studied. In 1977, at ITF SO AN SSSR an All-Union School was conducted on the rheology of polymers and oils, in which the leading rheological scientists of the Socialist countries took part.

At IPM AN SSSR in the last decade a wide complex of theoretical and experimental investigations has been conducted into the Toms problem, i.e., the reduction of the resistance of turbulent flows by small polymer additives.

Studies have been made of isothermal flow in channels, and rotational flow in boundary layers, allowing for viscoelasticity, degradation, etc.. The Toms effect is linked with the discrete-continuum representation of the structure of weak polymer solutions and with the formation of elastic-viscous nodules and combinations under certain conditions. This original conception has been confirmed in a series of tests.

One should note the contribution made to this problem by the rheological school, organized in the Volgograd Polytechnic Institute (VoPI). The rheological investigations performed there over a period of many years are linked to problems of heat and mass transfer in chemical-engineering processes and equipment (reactors, polymerizers, mixers, dispersers, and heat exchangers).

The original theoretical and experimental developments carried out at the Donets State University (DGU) have been favorably received. It has been established that very small additions of soluble soaps have an appreciable influence on the transport processes in suspension flows of water–coal slurries and mining pulp types.

Theoretical calculations of the complex heat transfer in circular tubes, accounting for dissipation and the rheological factor (viscoplastic and nonlinear-viscous liquids) beginning in the 1970's, have been conducted at the All-Union Scientific-Research, Planning, and Design Institute of the Petrochemical Industry (VNIIPKNeftekhim) (Kiev) and at Tad PI (Dushanb).

Starting in the 1960's theoretical investigations were carried out at ITMO AN BSSR into external transfer problems in nonlinear-viscous flowing liquids. The results of this broad class of investigation have been presented in the monograph by Z. P. Shul'man and B. M. Berkovskii "The Boundary Layer in Non-Newtonian Liquids." The theoretical and experimental investigations into rheodynamics and heat transfer in nonlinear-viscoplastic media flowing in tubes and channels were based on the most universal phenomenological four-constant rheological model (single-axis description)

$$\tau^{1/n} = \tau_0^{1/n} + (\mu_p \dot{\gamma})^{1/m},$$

where $\dot{\gamma}$ and τ are the velocity and the shear stress; τ_0 is the fluidity limit; μ_p is the analog of plastic viscosity; and m and n are parameters of the nonlinearity. The results of these developments have been generalized in a monograph by B. M. Smol'skii, Z. P. Shul'man, and V. G. Gorislavets, "Rheodynamics and Heat Transfer in Nonlinear-Viscoplastic Materials" (1970). Subsequent work was directed at discovering methods for exact, approximate and numerical solution of heat and mass-transfer problems in free and forced convection in rheologically complex liquids. The first classes of similarity solutions were found for flows in boundary layers, and rotational, film and jet flows.

A new equation was proposed for the rheological state of composite materials with polymer bond of the asphalt–concrete type. This model gives a qualitatively correct and quite realistic description of a group of basic thermal and mechanical properties of these materials: the instantaneous and the delayed elasticity, relaxation to stress, and the accumulation of plastic strains. With this model an analysis was made at ITMO AN BSSR of problems of heat and mass transfer in the stress–strain condition under dynamic load.

At ITMO AN BSSR a number of fundamental investigations were made in new and promising scientific and engineering directions, i.e., electro- and magnetorheology. From investigations into reverse exchange of rheological properties of dielectric suspensions a mechanism for the electrorheological effect was explained. It was discovered that such suspensions behave like weakly conducting dispersion systems in an electric field with variable structure, and this important law can be improved by investigating transport processes of different substances (momentum, mass, charge, thermal energy). It was discovered that the electric field intensity E has a very strong influence on one particular structural characteristic, the dynamic limit of fluidity.

The very important relation

$$\tau = \alpha_E E^2,$$

has been established, where α_E is a constant coefficient for a given suspension.

Most of the results pertaining to electrorheology have been published in the monograph "The Electrorheological Effect" (1972). A study has also been made of the influence of magnetic fields on transport processes in suspensions of ferromagnetic materials (the magnetorheological effect). It was shown that one can use magnetic fields for a directional influence on flows of suspensions of ferromagnetics, particularly in submerged and walled jets. For the first time the magnetothermal-invariant relation was obtained, which correlates the rheological characteristics of different composites over a wide range of temperature, rate of shear and magnetic field intensity. An anisotropy was discovered for thermal and electrical conductivities, induced by constant magnetic fields, as well as a radical intensification in heat transfer in rotating magnetic fields.

The statistical, amplitude–frequency, and phase characteristics of momentum transfer were obtained in different magnetorheological systems, subjected to the action of periodic and unsteady magnetic fields. On this basis the optimal magnetorheological suspensions were determined; and a number of high-accuracy high-speed auxiliary mechanisms, and hydroautomation and hydroactivation devices have been suggested, devised, and thoroughly investigated.

Valuable results have been obtained from theoretical and experimental investigations of unsteady transport processes in forced convection with anomalous-viscous liquids and weak polymer solutions. An analytical solution has been found to the problem of steady and unsteady convective heat and mass transfer in laminar flow of nonlinear-viscous liquids for different cases: a) a longitudinal flat plate, wedge and cone; b) a solid and a gaseous sphere; c) the inside wall of a tube; and d) a rotating disk.

Methods have been proposed for calculating the amplitude–frequency characteristics of unsteady transfer processes.

The groundwork for applications has been laid, the theory has been developed, and new methods for laboratory and seminatural measurements have been introduced into practice for the transport characteristics of rheologically complex liquids: electrodiffusion tension-anemometry, laser-anemometry, and acoustical probing. A method has been suggested and developed also for investigating the attenuation of turbulent diffusion near a wall, based on measurement of mass transfer under surge conditions.

New laws have been established for processes of heat and mass transfer in the wall boundary layer in clay suspensions, weak polymer solutions under transition from laminar to turbulent conditions and in developed turbulent flow, and in immersed jets and wakes. From this, methods have been proposed for control of the turbulent boundary layer, which would: a) substantially decrease the tangential friction stress; b) add to or increase the turbulent diffusion of material; c) reduce the level and the spectral density of wall pressure fluctuations; and d) redistribute the energy spectrum of velocity fluctuations in a turbulent free shear flow. In addition, the results of the scientific investigations conducted formed the basis for technical development in the scientific instrumentation area. Equipment developed at ITMO AN BSSR for measuring velocity and pressure fields in different liquids has permitted improvement in the technical processes involved in drilling and washing out of bores and has significantly expanded the capabilities of measurement instrumentation for probing the seas and the oceans.

An investigation has been made of the influence of the rheological factor on the thermophysical properties of amorphous and crystalline polymers of different kinds (polystyrene, polymethyl methacrylate, polyethylene, polypropylene, and polyvinyl chloride) under uniaxial strain conditions. These data were obtained in many development applications relating to processes for making polymers into fibers and tapes.

VIII. INVESTIGATION OF THERMOPHYSICAL PROPERTIES OF MATERIALS

This section gives a general outline of some of the directions and results of investigations in the determination of thermophysical properties of materials.

At the IVT AN SSSR, one of the leading centers in the country in the study of thermophysical properties of materials, a set of investigations has been conducted into the thermophysical properties of alkali metals and related multicomponent systems, which are heat-transfer agents and working substances for promising energy equipment; studies have been made of the thermophysical properties of dissociating substances like lithium hydrate, nitrogen tetroxide, etc.; experimental methods have been improved for determining thermophysical properties, and new experimental data have been obtained on the thermophysical properties of technologically important substances over a wide range of the state parameters. In March, 1973, under the auspices of the Presidium of the Academy of Sciences of the USSR, a Scientific Information Center was added to IVT AN SSSR, to deal with the thermophysical properties of pure substances (a thermophysical center), whose main objective is to organize a nationwide scientific-information system, dedicated to provide research institutes, engineering design schools and industrial organizations in the USSR with information on thermophysical properties of pure substances.

At ITF SO AN SSSR, investigations have been made into the thermophysical properties of liquid alkali metals, Freons, aqueous solutions of polymers and electrolytes, iron and other ferrous metals, optical and heat-radiative characteristics of a number of substances and materials, over a wide range of temperature and other parameters.

At ITMO, equipment has been developed for studying the thermophysical properties of materials of different aggregate states, and further development has been achieved of a number of techniques associated with constructing high-temperature facilities for measuring thermophysical properties of materials. The results of investigation of thermophysical properties of liquid-crystalline systems, and a group of heat-shield materials in steels, isotopic liquids and technically important gases have been transmitted to a number of organizations throughout the country which develop new types of structures and substances with predetermined properties.

At the Institute for Nuclear Energy (IYaE) detailed investigations into thermophysical properties of dissociating nitrous oxide have been made, and detailed tables have been constructed on the properties of dissociating nitrogen tetroxide.

At ITTF AN UkrSSR scientific foundations have been developed for heat measurement, and new heat-measurement instruments have been built and brought into service for precision measurements of thermal conductivity, heat capacity, emission and absorption properties of surfaces and coatings, and for determining energy effects in physicochemical and biological processes. These instruments have found wide use in scientific investigation and in industry, particularly for nondestructive material tests.

At LITMO a set of instruments has been constructed using methods appropriate for regular and monotonic conditions; these provide for the study of thermophysical properties of materials in the temperature range from −150 to 1000°C. Some instruments are intended for commercial and industrial production.

New methods and instruments have been developed for measuring arbitrarily time-dependent heat fluxes, and a wide range of investigations has been made to generate theoretical foundations for the measurement of unsteady temperatures using contact sensors.

Studies have been made of temperature fields in instruments, thermophysical properties of materials, and other matters, using an automatic system created at LITMO for collecting and processing information from a thermophysical experiment. This facility has appreciably improved the efficiency and the accuracy of measurements and has stimulated a systematic approach to the investigations.

The large number of unstudied substances, particularly mixtures and composite materials, and the limited possibilities for experimental investigations have made it an urgent matter to develop methods for predicting properties. In this regard physical and mathematical models have been developed in the problem laboratory of the thermophysics department of LITMO, headed by G. N. Dul'nev, for structures of heterogeneous systems, and computer methods have been developed for calculating physical and mechanical properties.

At ÉNIN theoretical and experimental investigations have been conducted into the thermophysical and transport properties of different media used in energy facilities.

Methods have been developed and programs have been created for computer calculation of coefficients of viscosity, heat conduction, diffusion and thermodiffusion of chemically reacting gas systems and alkali metal vapors. With these programs calculations have been made of the transport properties of combustion products of organic and special fuels, and also alkali metal vapors (Li, Na, K, Pb, Gs) over a wide range of temperature (up to 2000°K) and of pressure (up to 10 atm) variation.

The fundamentals have been developed for a kinetic theory of an aerosol plasma, allowing for the influence of an electric field. It has been established that the conductivity of an aerosol plasma in a strong electric field is lower than the value in a weak field.

Methods have been developed, within the framework of classical kinetic theory, for calculating inelastic ionizing collisions. New expressions have been obtained for the transport coefficients. It has been shown that the thermal conductivity of a partial ionized plasma, computed with allowance for a finite rate for the ionization processes, is different by a factor of 1.5-2.0 from the thermal conductivity computed without accounting for these processes. An experimental investigation has been made of the thermal conductivity of water at pressures from 100 to 1000 bar, at temperatures from 100 to 350°C. The thermal conductivity of steam has been determined in the temperature range from 450 to 700°C, at pressures from 100 to 1000 bar. The thermal conductivity of steam has been determined, beginning at 350°C on the subcritical 100- and 200-bar isobars. The data obtained have been used by the Soviet National Committee on the properties of water vapor to generate reference point tables.

In the Molecular-Physics Department of MGU new complex methods have been developed for investigating the thermophysical properties of metals, each allowing one to determine a set of basic thermophysical properties (thermal conductivity, heat capacity, thermal diffusivity) in the course of a single experiment.

Laws have been established relating absolute values and temperature coefficients of thermal conductivity and electrical conductivity. From an investigation of the thermophysical properties of liquid metals up to a temperature of 2000°K the dependence of the electrical conductivity of liquid metals on density has been established.

A set of studies has been made of the properties of liquids and gases, to determine new methods of measurement which would allow simultaneous determination of heat capacity and thermal conductivity over a wide range of temperature and pressure.

Using the law of thermodynamic similarity, methods have been devised for calculating the thermodynamic and kinetic properties of normal (nonassociated) substances, based on empirical data on the boiling temperature, the liquid density and the vapor pressure at temperature below the boiling temperature.

Relations have been found between the characteristic molecular structure parameter and the macroscopic parameters of a substance, from which, using the known molecular structure, one can determine a whole set of properties of liquids and gases, and, conversely, one can use a computer to choose the most suitable substance according to previously determined properties.

At MAI theoretical and experimental investigations have been made of thermophysical properties of alkali metal vapors, and methods have been developed further for experimental determination of the thermal conductivity of gases at high temperature, particularly an unsteady periodic heating method. An experimental study has been made of the thermal conductivity of a number of isocompounds to elucidate the influence of the isotopic effect on the thermal conductivity of gases, and a set of studies has been made in which existing experimental data on thermophysical properties of materials has been systematically and critically appraised.

At the Moscow Energy Institute (MÉI) an experimental determination has been made of a set of thermophysical properties of gases over a wide range of the state parameters, the experimental data on material properties has been analyzed and evaluated systematically, using computer processing, and experimental methods for determining the thermophysical properties of materials have been the subject of further methodological development.

At the State Institute of the Nitrogen Industry (GIAP) techniques have been developed, and an apparatus created for the measurement of thermophysical properties of materials at low temperature and high pressure, and experimental studies have been made of technically important materials.

At the Grozenskyi Oil Institute (GNI) the thermophysical properties of oils and oil products have been investigated over a wide range of the state parameters. A number of problems of technique have been solved, e.g., the original structural design of measuring cells for investigating thermal conductivity by the heated wire and coaxial cylinder methods, calculation of convective heat transfer during measurements of the thermal conductivity of liquids, and so on.

The results of an experimental investigation of the thermophysical properties of oils and oil products have been presented in detailed tables, which have been sent to branches of the Institutes of the Ministry of the Petroleum and Chemical Industry of the USSR (Minneftekhimprom). The test data on density, heat capacity, viscosity and thermal conductivity of oils and oil products, obtained at the Institute, constitute the basis for the data collected by the Center (the VNIIPKNeftekhim, Kiev) for the unique branch automation system of thermophysical retrieval (AVESTA-1) and will be used to prepare a data bank on the properties of oils and oil products.

IX. HEAT- AND MASS-TRANSFER PROCESSES IN LASER-ACTIVE MEDIA AND IN A HIGH-TEMPERATURE PLASMA

The intensive development of investigations of transfer phenomena in laser-active media and high-temperature plasma is one of the most remarkable characteristics of the development of science and technology in the last decade. The progress in the development of high-power lasers and the technology of laser processing of materials has significantly increased practical interest in this field and has caused it to be one of the most urgent problems in the scientific and technical revolution.

At the P. N. Lebedev Institute of Physics of the Academy of Sciences of the USSR (FIAN SSSR) principles have been evolved for constructing gasdynamic lasers, where the inverse population of the medium is attained by rapid cooling during discharge through a supersonic nozzle. Laser systems of this type are the most promising for obtaining high-power fluxes of continuum optical radiation. The experimental investigations of physical processes in gasdynamic lasers with selective thermal excitation during mixing in a supersonic flow, accomplished at ITPM, have shown that it is possible to increase substantially the gain and the overall efficiency of a gasdynamic laser (GDL). At present investigations in this area are being developed intensively at I. V. Kurchatov Institute of Atomic Energy (IAÉ), ITMO AN BSSR, TsAGI, IPM AN SSSR, and a number of establishments of the Academy of Sciences of the USSR.

Significant progress has been made in developing straight-through gas-discharge lasers with convective cooling of the working media (FIAN SSSR, IPM AN SSSR, IAE, ITPM SO AN SSSR). The intensification of heat transfer processes in straight-through laser systems allows small-scale closed-cycle equipment to be developed, with output power level $\geqslant$ 1 kW, and these hold out promise for engineering applications. Investigations are being conducted on a broad front into the role of plasma-chemical reactions in the working region of convective gas-discharge lasers using carbon dioxide. There is substantial interest in studies of the electrogasdynamic lasers using CO, which have higher efficiencies, and combined systems which use a combination of cryogenic technology and high-level adiabatic cooling of the working medium, excited by an electrical discharge.

A series of theoretical and experimental studies has been made, dealing with phenomena of heat and mass transfer in straight-through chemical lasers which use reactions forming vibrationally excited molecules. Basic problems are being examined in creating an atomic reactor—laser based on a gas-phase reactor (FIAN SSSR, ÉNIN). It has been established that recombination nonequilibrium can be achieved by efficient pumping of the laser medium.

Basic laws have been determined for the process of energy exchange between the electronic and the gas components in a laser-active plasma of gas-discharge and electrical-ionization lasers at atmospheric pressure (FIAN SSSR, IAÉ, ITPM SO AN SSSR, NIIÉFA, ToPI, and ITMO AN BSSR). The results of these studies allow one to determine the optimal structural features and operating conditions for high-power continuous and pulsed laser systems.

Special mention should be made of studies devoted to the interaction of high-power laser radiation with matter [FIAN SSSR, IAÉ, IYaF, and S. I. Vavilov Institute of Physical Problems (IFP)]. In the last decade the phenomenon of optical breakdown in gases has been discovered and investigated in detail, the basic problems of laser thermonuclear synthesis have been formulated and subjected to experimental check, the basic laws have been established for processes of gas-laser cutting, welding and material processing, and problems associated with building an optical plasmatron and a laser rocket motor have been studied. In the course of experimental work in this area a high-temperature plasma with extremely high values of density has been obtained and investigated, and a whole series of new phenomena has been discovered, associated with phase transitions in material subject to high-power pulse heating.

The newness of the topic explains the absence of monographs dealing with the problem of heat and mass transfer in laser systems. The basic results of work accomplished in the Siberian Branch of the Academy of Sciences of the USSR have been collected systematically in the collection "Gas Lasers", edited by R. I. Soloukhin and V. P. Chebotaev (1977). Work of a review nature on related topics has been published systematically in FIAN SSSR reports. A series of topics concerning interaction of laser radiation with matter is treated in the monograph by Yu. P. Raizer "A Laser Source and Propagation of Discharges" and in the book "The Action of High-Power Radiation on Metals" by S. I. Anisimov, Ya. A. Imas, G. S. Romanov, and Yu. V. Khodyko.

At ITMO AN BSSR studies have been made of kinetic processes and transfer phenomena in gasdynamic and straight-through gas-discharge lasers. The influence of gasdynamic perturbations on the operating conditions of the GDL with selective thermal excitation has been investigated. An effective system has been developed for obtaining an elongated spark discharge for preionization of the working medium of gas-discharge lasers at atmospheric pressure. The influence of initial conditions on the development of a uniform discharge in the typical geometry of lasers with transverse pumping has been investigated. It has been established theoretically and experimentally that there is a definite area of values of initial electron density and electric field strength where volume discharge conditions are obtained, and a simple physical model has been developed which can explain a number of typical effects observed when one generates a glow discharge in dense gases.

Studies have begun of the influence of heat- and mass-transfer processes in near-electrode layers on the stability and uniformity of a discharge used for pumping straight-through gas-discharge lasers at atmospheric pressure. The role of gas density gradients when a heated cathode is used has been analyzed. An investigation has been made of the influence of easily ionized additives, introduced in the cathode region of the discharge gap, on the nature of the discharge. It has been established that the presence of these additives leads to an improvement in the uniformity and an increase in the stability of a volume discharge. An analysis has been made which shows that the basic role here is played by processes of photoionization of the additives, occurring both at the pre-ionization stage, and also during development of the discharge.

The data obtained allow one to determine optimal conditions for the operation of continuous and pulsed laser systems, and can be used in the development of lasers for engineering applications.

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This brief and far from complete list of investigations into heat-, and mass-transfer processes and of some of the results of basic and applied work shows considerable progress in the investigations listed, that the part played by computer technology has increased, and that computers are being used to solve contemporary industrial problems.