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HEAT- AND MASS-EXCHANGE SCIENCE IN BELARUS: FROM A. V. LUIKOV TO THE PRESENT DAYS

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Works on heat and mass exchange, performed at the scientific institutions of Belarus, have been reviewed briefly.

More than half a century has passed since the day of formation of the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus (former the Institute of Power Engineering of the BSSR Academy of Sciences). The works of the initial period of existence of the Institute were aimed at solving the primary tasks of the Republic's national economy; the energy balance of the BSSR and the cadaster of its water resources were composed for the first time; investigations on the use of peat and products of its processing and of the waste of the forest and wood-working industries in the energy balance were begun. The problems of drying of materials began to be widely solved.

With the arrival of A. V. Luikov at the Institute in the late 1950s-early 1960s, the subjects of investigation of the Institute were transformed, which was caused by the necessity of creating scientific foundations of heat- and mass-exchange technological processes and apparatuses in power engineering, mechanical engineering, space technology, and other branches of the national economy. The Heat and Mass Transfer Institute became the head organization in the USSR and the coordinator of investigations of interrelated heat and mass exchange in capillary-porous bodies, disperse systems, rheological media, aerothermooptical devices, and generators of a low-temperature plasma.

Conjugate Problems of Heat Exchange. In investigating the problems of convective heat exchange between a solid body and a liquid or gas flow, one uses, as a rule, boundary conditions of the third kind (Newton law), i.e., the conditions of proportionality of the heat flux near the wall q_w to the difference between the temperatures of the wall T_w and the incoming flow T_∞:

$$q_w = \alpha (T_w - T_\infty) . \tag{1}$$

The proportionality factor α is called the coefficient of heat exchange; in determining it theoretically, one usually assumes that the conditions on the wall are specified and constant.

However, T_w cannot be assumed to be a constant in high-intensity processes; therefore, it is unacceptable to use the Newton law (1), when the dependence of T_w on the longitudinal coordinate x is prescribed in advance. This is clear from Fig. 1 [1]. The use of expression (1) and the Fourier law

$$q_w = -\lambda \left.\frac{\partial T}{\partial y}\right|_w \tag{2}$$

can lead to completely different results, in particular, the Nusselt number Nu = $\frac{\alpha\delta}{\lambda}$ can be a negative, i.e., it loses its physical meaning.

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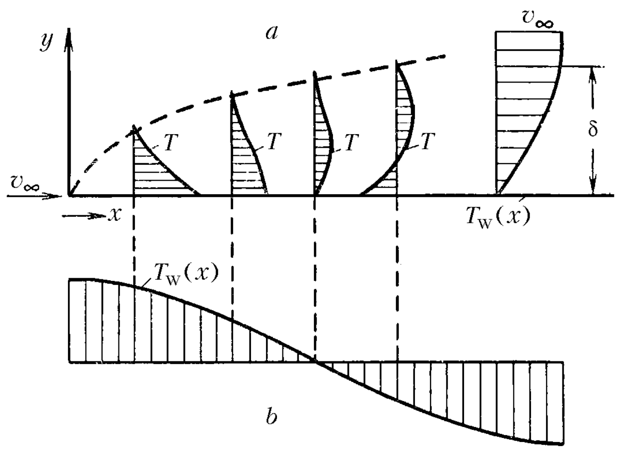

Fig. 1. Temperature profile in the boundary layer (a) at a prescribed $T_w(x)$ (b).

In stationary heat exchange, the use of prespecified conditions at the body–liquid boundary has meaning in the cases of extremely high and extremely low thermal conductivities of the solid body. Therefore, strictly speaking, the conditions at the interface cannot be specified; they must be obtained by simultaneous solution of the equations of propagation of heat in the solid body and the liquid together with the equations of motion, and the conditions of equality of the temperatures and the heat fluxes must be specified at the body–liquid boundary. Such a formulation of the problem of heat exchange is called conjugate.

Formulation of the problems of convective heat exchange as conjugate ones in the nonstationary case is of particular importance. The expediency of such a formulation was proved for the first time in [2]. As a result of the original solution of a conjugate problem of convective heat exchange, it was shown that the course of the process of nonstationary heat exchange depends on both the characteristics of a liquid flow and the properties of a solid body. In particular, the dependence of the heat flux (and consequently of the Nusselt number) at the solid body–liquid boundary on time and on the characteristics of the solid body was confirmed experimentally. Therein lies the difference of the process of nonstationary heat exchange from that of stationary heat exchange where the dependence of the process on the properties of the liquid and the body manifests itself only when the thermophysical characteristics of the body and the liquid do not differ very strongly.

Heat and Mass Exchange in Capillary-Porous Bodies and in the Processes of Drying. The processes of heat and mass transfer in porous media are the basis for highly diverse industrial technologies and natural phenomena. Widescale investigations of interrelated heat and mass transfer in unsaturated capillary-porous bodies with allowance for phase transformations were carried out under the supervision of A. V. Luikov.

The well-known system of equations of A. V. Luikov [3]

$$\frac{\partial T}{\partial t} = \frac{1}{c_p \rho} \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\psi Q}{c_p} \frac{\partial u}{\partial t},$$

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left(\chi \frac{\partial u}{\partial x}\right) + \chi \delta' \frac{\partial T}{\partial x}$$

is widely used for description of the processes of drying.

Based on the methods of drying and heat treatment of materials developed and the study of the hydrodynamics of the process, the important national economic problem of creation of high-intensity methods of drying of grain was successfully solved. The operating principle of modern grain dryers lies in using oscillating temperature regimes in combination with contact heat and mass exchange in the bed of a granular material. New techniques for drying of different materials and methods of description of heat and mass transfer in colloidal porous media with allowance for sorption and desorption have been proposed recently.

Investigation of the aerodynamics of swirling flows and the kinetics of high-intensity drying of solutions and suspensions led to the creation, under the supervision of P. S. Kuts, of the technology of drying of liquid materials;

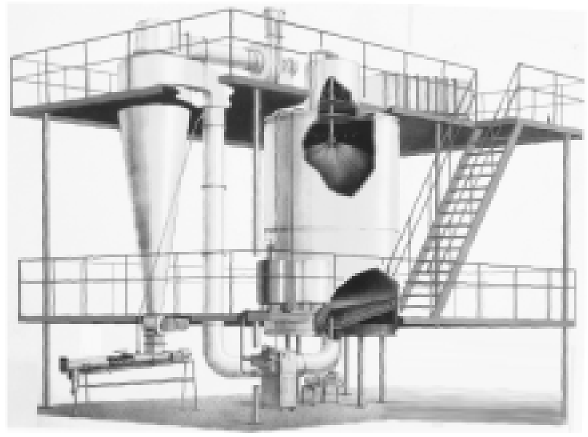

Fig. 2. Spray dryer: evaporated-moisture output 300 kg/h; volume of the drying chamber 24.6 m^3; power consumption 23 kW·h; inlet temperature of the heat-transfer agent 160^oC, outlet temperature $65–70^oC$; moisture removal 12.2 kg/(m^3·h); overall dimensions $6 \times 8 \times 8$ m.

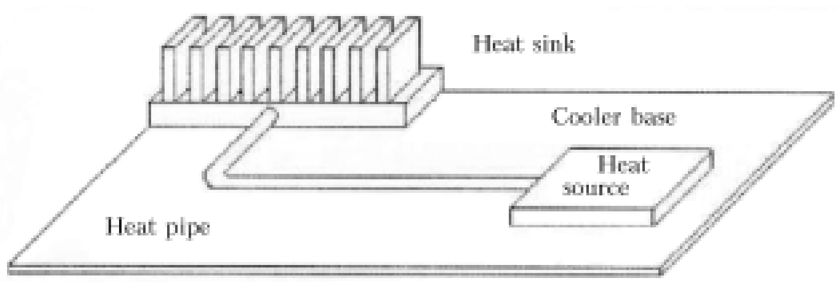

Fig. 3. Heat pipe for cooling of semiconductor devices.

Fig. 4. Balloon for storage and transportation of low-pressure methane in the bound state; it is manufactured from thin-walled steel tubes filled with sorbent.

this technology was implemented in the design of a spray dryer (Fig. 2). A method of drying of medical preparations was developed based on the investigations of heat and mass transfer in two-phase flows with combined supply of heat. In [4], schematic diagrams of the drying equipment have been given and technologies developed at the A. V. Luikov Heat and Mass Transfer Institute for drying of moist materials have briefly been described.

Study of the regularities of the process of transfer in capillary-porous structures in the presence of phase transformations and the creation of new types of heat pipes enabled us to solve problems of intense heating, cooling, and thermal stabilization of products operating under space conditions, when large variable thermal loads occur. A heat pipe for cooling of semiconductor devices has been created (Fig. 3).

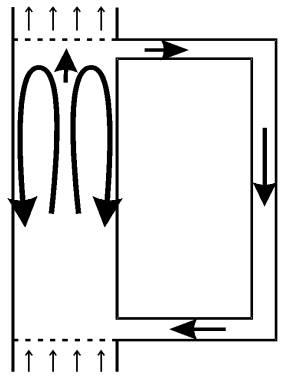

Fig. 5. Diagram of a circulating fluidized bed.

A new mechanism of utilization of heat with the use of solid sorbents in which the combined action of chemical reactions and physical adsorption is carried out has been proposed, which makes it possible to create original designs of heat engines (refrigerators), thermal pumps (thermocompressors), and thermotransformers. A 3-kW sorption thermal pump has been developed for heating of air and cooling of water. The dynamics of the process of sorption and desorption in porous sorbents has been investigated with allowance for phase transitions; technical implementation of the results obtained makes it possible to significantly improve the efficiency of the heat engines designed and to create tanks for storage of natural gas in the adsorbed state (Fig. 4) (L. L. Vasil'ev et al.) [5].

The kinetic theory of flow of gases in porous media with allowance for evaporation (condensation), the presence of moving adsorbed layers in capillaries, and a deepened boundary of evaporation has been developed based on solution of model kinetic equations. The applicability range of the existing phenomenological relations — Fick's law, the expression for the Stefan flow, and the Poiseuille formula — have been considered (N. V. Pavlyukevich et al.) [6].

Processes of Heat and Mass Exchange in Disperse Systems. Intense investigations in this field were initiated in Belarus in the late 1950s by S. S. Zabrodskii and his disciples. Emphasis was on the study of fluidization hydrodynamics. Different modifications of a fluidized bed — fluidized, spouting, or pulsating — have been developed to obtain properties prescribed in advance.

Investigations of the hydrodynamics and heat exchange in disperse media in the presence of phase and chemical transformations have been performed under the supervision of A. V. Borodulya, which made it possible to develop methods of mathematical and physical modeling of the processes in fluidized-bed reactors and to develop the optimum instrumental design based on them. A mathematical model of nonstationary mixing of particles in a circulating fluidized bed, which allows for the actual structure of particle fluxes in the riser (upward flow in the bed's core, downward flow at the riser walls) has been proposed (Fig. 5). This model satisfactorily describes experimental data.

Based on the results of a complex investigation of the heat and mass transfer in a fluidized bed in combustion of solid particles, the scientific foundations of low-temperature burning of different types of solid fuel have been developed, which made it possible to create high-efficiency boilers with a fluidized-bed furnace [7].

N. V. Antonishin and the staff of the Laboratory of Heat-Exchange Processes and Apparatuses have investigated the transfer of heat by a high-temperature dispersed heat-transfer agent and have developed and introduced the techniques of high-speed, oxidation-free heating of metal in the dispersed layer of the heat-transfer agent. The results obtained are used to calculate and design the corresponding furnaces; the metal surface is not oxidized.

The technology of processing of worn-out tires by the method of steam thermolysis has been proposed. The method is, in essence, special heat treatment of the rubber waste by a superheated steam, as a result of which we have the destruction of rubber with the formation of solid, liquid, and gaseous phases (activated carbon, fuel oil) [8].

Investigations of the mass transfer in natural disperse systems are being carried out under the supervision of I. I. Lishtvan; the mobility of moisture in the soil as a function of the structure of the latter, its rheological properties, and the kinetic phenomena at the phase boundary is being studied [9].

Technologies and Thermophysics of Metallurgical Processes. The Belarusian scientific school in this field as applied to units functioning in the so-called great metallurgy was, in essence, generated at the instant the Belarusian Metallurgical Plant (BMP) was put into operation in October 1984, when steel was melted at it.

Fig. 6. Setup of controlled water–air cooling of metallic products.

The processes of molding of continuous castings and subsequent heating in mill furnaces and heat treatment of bars in controlled-cooling pits have been investigated under the supervision of Professor V. I. Timoshpol'skii. The process of continuous casting significantly differs from the traditional technique of pouring and is one of the most progressive technological processes in ferrous metallurgy. Its advantages include the attainment of a homogeneous crystal structure, improvement in the quality of steel, and the possibility of combining continuous casting and rolling in a single technological line.

Mathematical modeling of the process of solidification of an ingot must allow for the fact that most of the commercial grades of steel represent alloys crystallizing in the temperature interval between the liquidus T_{liq} and the solidus T_{sol}. In this case, the crystallization front represents, instead of the phase interphase, a spatially distributed system (linkage between the dendrite crystals and the melt), which is commonly called a two-phase zone. The release of the crystallization heat is "smeared" in the range T_{liq}–T_{sol}; therefore, the boundary-value problem of heat conduction is formulated with allowance for the presence of the heat source in the heat-conduction equation rather than in the Stefan formulation:

$$\rho c_p \frac{\partial T}{\partial t} = \text{div}\,(\lambda\ \text{grad}\ T) + \rho Q \frac{\partial \overline{\Psi}}{\partial t}\,. \tag{3}$$

The parameter $\overline{\Psi}$ is determined by the kinetics of growth of the crystals, but for fairly massive ingots we can assume that the fraction of the solid phase is determined from the equilibrium diagram of state. Then we have $\partial\overline{\Psi}/\partial t$ = $(d\overline{\Psi}/dT)(\partial T/\partial t)$, and we can use the effective specific heat of the alloy in Eq. (3).

Mathematical models of heating of cylindrical ingots in rotary-hearth annular furnaces have been developed with allowance for the transfer and absorption of radiation in the furnace's working space [10]. Application packages for calculation of the processes of solidification, cooling, and heating have been created based on the results of the investigations; these packages have been offered to the BMP.

Mathematical models based on the principle of optimization for the most substantial figure of merit, from the minimum of scaling, fuel flow rate, decarbonization, etc., have been created in investigating the processes occurring in heating of billets in the mill furnace.

Generalization of the experience of investigations in the field of the theory and technology of metallurgical processes as applied to great metallurgy has been reflected in the three-volume publication "Steel Ingot" [11].

For the first time in the theory and technology of production of cord grades of steel, a complex methodology was used; the methodology covers the investigation of the main branches of production of metal cord: melting, continuous casting, furnace heating, and patenting. As a result, the concept of melting of high-carbon grades of steel has been developed to obtain superstrong modifications of metal cord with the use of new mix materials. A complex mathematical model of melting in a superpower arc furnace, which allows for the physicochemical, thermal, and mass-exchange processes, has been created.

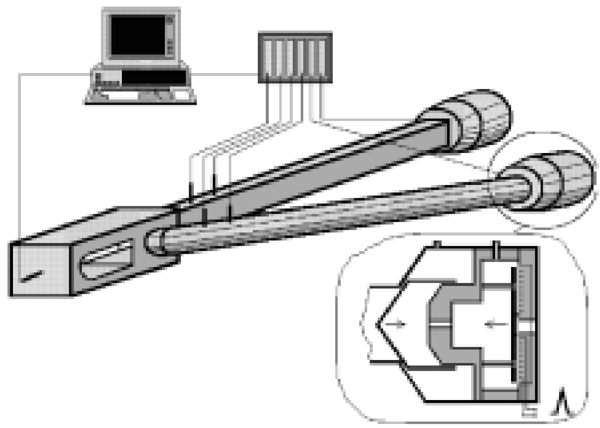

Fig. 7. Diagram of the setup with shock tubes.

The technology and setup of controlled water–air cooling have been proposed for replacement of environmentally unsafe quenching media (oils, polymer solutions, and others) in thermal strengthening of metal products (M. L. German and M. S. Zheludkevich) (Fig. 6).

Theoretical and experimental investigations in the field of mastering of the latest technologies and units are carried out at the A. V. Luikov Heat and Mass Transfer Institute at present to obtain seamless pipes from carbon and alloy grades of steel for the oil and gas industry and power engineering (supervisors of the project M. V. Myasnikovich and V. I. Timoshpol'skii).

Hydrodynamics and Heat Exchange in Rheologically Complex Systems. An important role in many modern technologies is played by the processes of heat and mass exchange in the so-called non-Newtonian media in which the apparent viscosity is a function not only of the temperature or the pressure but of the rate of shear as well.

At the A. V. Luikov Heat and Mass Transfer Institute, rheophysical investigations are being carried out under the supervision of Z. P. Shul'man. A new phenomenological equation of rheological state of nonlinearly viscoelastic media [12]

$$\tau^{1/n} = \tau_0^{1/n} + (\mu_p \dot{\varepsilon})^{1/m} \tag{4}$$

has been formulated, which generalizes the well-known linear model of Shvedov and Bingham $\tau = \tau_0 + \mu_p \dot{\varepsilon}$ ($n = m = 1$).

Electrorheological investigations are being intensely developed; they make it possible to create new models of high-speed dielectric-rotor micromotors not having traditional windings and commutators, where the rotational velocities are controlled just by the electric-field strength. Magnetorheological investigations are being carried out in parallel. Their results have been used in developing a unique technology of polishing of nonmetallic materials.

Noteworthy is the cycle of works on biomedicinal rheology, in particular, on investigation of the influence of the rheological factor of the blood flow in hyperthermia and photodynamic red-light irradiation.

Processes of Transfer in Nonequilibrium Media. On the initiative and under the supervision of R. I. Soloukhin, a complex of investigations in the field of gasdynamic processes and heat transfer in laser-active media has been performed and the optical methods for investigation of macroscopic and molecular processes in gas lasers [13] and the foundations of the method of selective thermal pumping ensuring a substantial improvement in the efficiency of gasdynamic lasers have been developed.

Interesting results have been obtained in investigating detonation combustion on a unique setup with shock tubes. Procedures enabling one to accelerate the process of combustion and to ensure the transition of combustion to detonation are developed; the energy released in combustion of the fuel itself is used for creation of a shock wave (Fig. 7). Such investigations are the first step toward creating detonation motors that can be used, for example, in the rocket industry.

Original methods of diagnostics of the density, velocity, and temperature fields in the flows of gases, liquids, and a plasma based on speckle photography and speckle interferometry have been proposed (N. A. Fomin) [14].

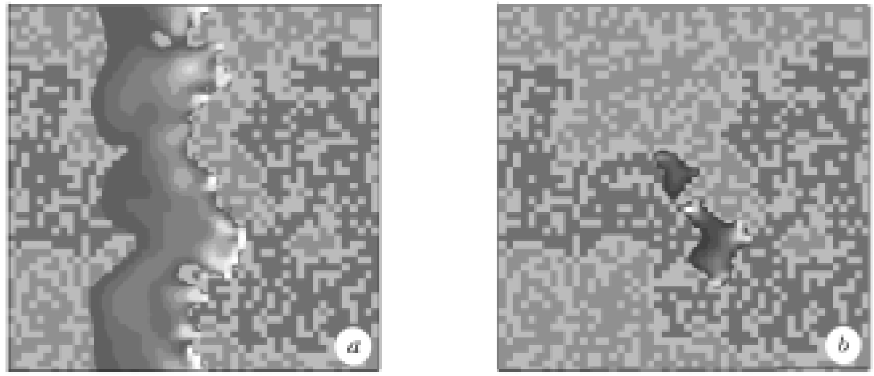

Fig. 8. Inclination instability of the front of filtration combustion of a methane–air mixture.

Fig. 9. Frontal (a) and percolation (b) regimes of propagation of the combustion wave in a heterogeneous mixture of the fuel and the inert component.

Filtration Combustion. A notable advance has been made under the supervision of S. A. Zhdanok in investigations of the processes of transfer in filtration combustion of gaseous substances in porous media, which play an important role of the regenerator of thermal energy. The conditions of attainment of the superadiabatic effect that is produced by addition of the energy generated earlier in the superincumbent part of a porous body have been formulated, i.e., part of the heat of the reaction products returns to the reaction zone because of the feedbacks. It has been shown that we have the following relation between the maximum (superadiabatic) temperature in the combustion zone T_{max} and the velocity of motion of the reaction front U_r:

$$T_{max} = T_0 + \Delta T_{ad} \frac{W_{th}}{W_{th} - U_r} . \tag{5}$$

A systematic presentation of a wide range of problems of filtration combustion of gases has been given in [15]. In it, in particular, a detailed investigation of the stability of the filtration-combustion front has been presented, an analysis of the joint influence of thermal and hydrodynamic factors on the stability of the front has been performed (Fig. 8), and a qualitative method of analysis — the method of competition of flows — has been developed. The inhomogeneity of the convective flow or the filtration field, which is caused by the inhomogeneities of the porous body and the temperature field, is a disturbing factor for the combustion front. Conductive heat fluxes tending to compensate for the temperature inhomogeneities in the system are a stabilizing factor.

If the second reagent in the porous body is in the condensed phase, we are dealing with the filtration combustion of the condensed phase. As a result of the theoretical investigation of the combustion of heterogeneous condensed systems, the features of this process due to the stochastic distribution of the fuel in space have been revealed. The parameters characterizing the conditions of transition from the frontal regime of propagation of the combustion wave to a percolation regime have, in particular, been determined and the conditions of existence of a percolation regime of combustion have been established (Fig. 9) [16].

A large complex of works on *aerothermooptics* has been carried out in the field of free-convective heat exchange under the supervision of O. G. Martynenko [17]; investigations of the gasdynamics and heat exchange of a wide class of shear flows of a gas with different conditions in intricately shaped channels have been performed. The investigations carried out and the development of efficient methods of control of laser radiation propagating in thermally inhomogeneous media made it possible to offer new aerothermooptical devices.

Based on the experimental and theoretical investigations of many years carried out in the field of the aerodynamics of convective heat exchange in chimney-type evaporative cooling towers, it has been established that creation of vortex flows inside the cooling tower with the use of rotators with a vertical axis makes it possible to substantially improve the thermal efficiency of the cooling towers by intensification of the processes of heat and mass exchange in evaporative cooling of a circulating water. This leads to a decrease in the temperature of the recycled water, particu-

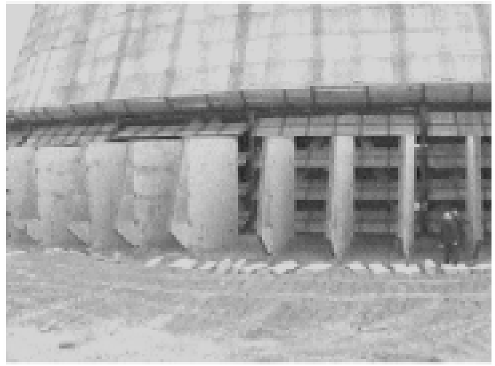

Fig. 10. Production prototype of an aerodynamic vortex generator.

larly in the case of moderate and strong winds near the cooling-tower mouth (Fig. 10). As a result of the joint work with the "Belénergo" Concern carried out, the cooling tower at Minsk Thermoelectric Plant TÉTs-4 has been modernized.

Works on an analysis of the environmental effect of chimney-type evaporative cooling towers on the environment have also been performed. It has been shown that the greatest hazard to the population living in the nearest areas is acoustic rays with frequencies lower than 10 Hz, radiated from the chimney-type cooling towers, propagating in the direction of the wind, and arriving at the cone of the cooling tower: they experience strong refraction in the acoustic channel formed by the cone because of the difference in the temperatures of the cone's vapor–air mixture and the ambient air. Also, the problem of propagation of moisture in dropping form substantially influencing the microclimate of the neighboring areas from chimney-type evaporative cooling towers has been solved [18, 19].

Heat and Mass Transfer in a Low-Temperature Plasma and under the Action of High-Concentration Energy Fluxes on Materials. Here we should primarily note [20], which is devoted to investigations of the interaction of laser radiation with a substance; the investigations were carried out at the Institute of Physics of the National Academy of Sciences of Belarus. In this fundamental monograph, the thermal mechanism of destruction with allowance for the kinetics of evaporation of the substance and the hydrodynamic regime where the internal vapor energy exceeds the evaporation heat have been considered.

At the A. V. Luikov Heat and Mass Transfer Institute, theoretical investigations of the interaction of high-power-radiation flows with porous materials have been carried out, the cases of laser and electronic heat sources have been considered, and mathematical models describing temperature fields in media with a high porosity have been constructed. A calculation procedure has been developed and data on the thermodynamic properties and the spectral, group, and average coefficients of absorption of air, the atmosphere of Mars, a water vapor, and a silica vapor have been obtained. The range of temperatures 10^3–10^7 K is characteristic of a molecular and dissociated gas and of a low-temperature and multiply charged plasma [21].

In the field of plasma chemistry, the scientific foundations have been developed and the equipment for plasmachemical processes of synthesis of nitric oxides from atmospheric air in production of ammonia and processing of a phosphatic raw material has been manufactured under the supervision of O. I. Yas'ko. The technologies of processing of powdered substances in plasma reactors, obtaining oxides of rare-earth elements and thermally stable pigments, and processing of a toxic and radioactive waste have been created [22]. The technologies of obtaining steel directly from ore pellets without using coke have been developed, and plasmatrons for a semicommercial unit of power 1 MW and of output of 20,000 tons of steel per year have been manufactured (Fig. 11). Promising are the technologies of production of superfine mineral fibers of steel, quartz, and basalt and hollow steel and ceramic microspheres in an electric-arc nitrogen plasma. Hollow ceramic microspheres, owing to the unique combination of a spherical shape of controlled dimensions, a low density, and a high strength, are the most important technological fillers of composite materials.

An important direction is experimental and theoretical investigation of heat and mass transfer in interaction of high-temperature gas and radiation flows with thermal protective materials, which made it possible to create high-power gasdynamic units (plasmatrons, a plasma accelerator) on which the process of ablation was investigated and

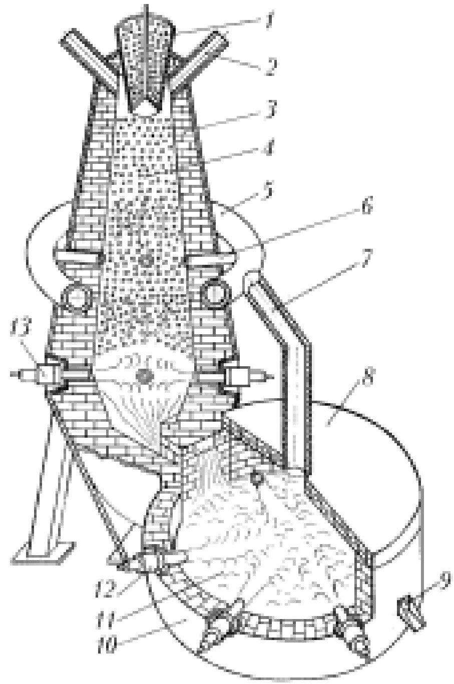

Fig. 11. Structural scheme of the reactor for direct production of liquid steel: 1) charging device; 2) gas vents; 3) refractory lining; 4) shaft; 5) annular gas collector; 6) gas ducts; 7) by-pass; 8) cover of the postreduction chamber; 9) tap hole; 10) postreduction chamber; 11) molten metal; 12) plasmatrons of the postreduction chamber; 13) shaft plasmatrons.

thermal protective materials for spacecraft were tested (A. G. Shashkov and F. B. Yurevich). Such investigations were considerably stimulated by the publication of [23] (1976), in which the advances in the field of aerodynamics and heat and mass exchange as applied to the design and calculation of thermal protection were generalized.

Heat Exchange in Turbulent Media. Two directions of theoretical investigations — development of semiempirical turbulence models and statistical theory of turbulence — were developed in parallel at the Laboratory of Turbulence (A. V. Luikov Heat and Mass Transfer Institute) under the supervision of B. A. Kolovandin. Much attention was given to experimental study of the features of evolution of nonisothermal turbulent flows, including the cases in the presence of chemical reactions and flows with polymer additions.

Most atmospheric and oceanic wake flows are anisotropic, since they develop under the conditions of stratification of one average scalar parameter (density, saltiness, temperature) or several parameters. The anisotropy of turbulence causes some interesting effects, for example, internal gravitational waves, to appear. A theory of generalized-homogeneous turbulence stably stratified by the density of the liquid has been presented in [24]. The problems of mixing of a scalar contaminating substance in stratified wakes are important practical problems in which one must allow for the anisotropy of turbulence.

In problems of turbulent mixing and diffusion combustion (whose rate is determined mainly by the rate of turbulent mixing of the components to the molecular level), very fruitful at present is the direction where the density distribution function of the scalar and its gradient is used. A theory of micromixing in turbulent reacting flows (based on the equation for the joint density distribution of the scalar and its gradient) has been presented in [25].

Computational Thermography. The principles and scientific and technological foundations of computer thermography have been created (V. L. Dragun and S. A. Filatov); it combines a complex of methods, software, and hardware based on recording and measurement of the radiation of objects in the infrared, submillimeter, and visible spectra, efficient processing of information in the computational process, and experimental investigation of thermophysical and optical parameters. A system of early computer diagnostics of breast pathologies has been developed; it is based on interference-free algorithms of dynamic formation of invariant signs analyzed by the expert system [26].

Based on the methods of computer thermography of high temperature resolution, correlations between the measured and modeled temperature fields of the working assemblies of machines and the structural-mechanical parameters have been established. The concept of nondestructive thermographic inspection of elements of heat exchangers and a highly informative method of thermal (thermographic) flow detection of heat insulation of structural elements have been developed.

Investigation of Thermophysical Properties. Methods of complex investigation of the coefficients of thermal conductivity, thermal diffusivity, and heat capacity of different materials in a wide temperature range have been developed under the supervision of A. G. Shashkov. Procedures of determination of the thermophysical properties of decaying materials have been proposed [27]. Extensive investigations of the thermophysical properties of gases, liquids, and solid bodies have been performed. Formulas for the effective coefficients of nonmetallic and metallic granular porous materials with allowance for contact heat conduction, the transfer of heat in a microgap, and radiant heat transfer have been given in [28].

Systems of Passive Removal of Heat. Important experimental results have been obtained by the specialists of the Institute of Problems of Power Engineering of the Joint Institute of Energy and Nuclear Research (Sosny) of the National Academy of Sciences of Belarus for substantiation of the system of passive removal of heat [29]. The investigations were carried out on a thermophysical bench modeling the first and second circuits of a nuclear power plant and different loops of removal of heat. The total installed power of the electric heaters of the experimental setup was 1.5 MW, whereas the maximum elevation was at the level of 48 m. As a result of the investigations carried out, the concept of a totally passive emergency-cooling system has been developed, which combines the advantages of evaporative systems and systems with removal of heat to the ambient medium and makes it possible to combine the peak increase in heat removal at the initial step of an accident with the possibility of an unlimitedly long shutdown cooling of the reactor. The results of the investigations presented became part of the substantiation of the Russian project AÉS-92 performed on the basis of a VVER-1000 reactor unit.

Investigations on heat and mass transfer are being actively carried out at present in Belarus within the framework of the State Programs "Hydrogen Power Engineering" and "Nanomaterials and Nanotechnologies," according to which the head organization is the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus.

NOTATION

c_p, heat capacity; Nu, Nusselt number; Q, heat of phase transition; q_w, heat flux on the wall; T, temperature; T_0, ambient temperature; ΔT_{ad}, adiabatic thermal effect of the reaction; t, time; u, moisture content; U_r, velocity of motion of the reaction front; v_∞, velocity of the incoming flow; W_t, velocity of the thermal wave; x, y, coordinates; δ, boundary-layer thickness; δ', thermogradient coefficient; $\dot{\varepsilon}$, rate of shear; λ, thermal conductivity; μ_p, coefficient of plastic viscosity; ρ, density; τ, shear stress; τ_0, limit shear stress; χ, moisture diffusivity; $\overline{\Psi}$, volume fraction of the solid phase in the two-phase zone; ψ, criterion of phase transformation. Subscripts: w, wall; liq, liquidus; sol, solidus; th, thermal; max, maximum; ad, adiabatic; r, reaction; p, plastic.

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