THERMOPHYSICS: PROBLEMS AND PROSPECTS

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Thermophysics is a branch of physics concerned with energy and mass transfer in thermodynamic systems accompanied by dissipation and corresponding entropy increase. The phenomenological concepts follow from thermostatics and thermodynamics of irreversible processes. Practical applications involve a wide range of microphysical concepts derived from electrodynamics, molecular physics, hydrodynamics, gas dynamics, and other branches of physics.

Modern thermophysics developed as a scientific line in the 1950s and 1960s and is now represented by a series of institutes and specialized laboratories. The phenomena involve complicated interactions between thermodynamic, gas-dynamic, and electrodynamic processes in solids, liquids, gases, and plasmas. Often, these are complicated by physicochemical transformations, marked disequilibrium, and physical-property variability [1].

The present survey deals with thermophysics on the basis of the main results obtained at the Institute of Thermophysics, Siberian Branch, Academy of Sciences of the USSR, in the period of over twenty years for which it has existed.

Thermophysics has two related divisions, which cover researches on irreversible energy and mass transfer on the one hand and the thermodynamic (caloric) and transport features of matter on the other. Researches on thermodynamic and transport parameters (thermophysical properties) are of practical significance and are related primarily to obtaining reliable information on the properties of new coolants, working bodies, and constructional materials.

New evidence has been obtained that has been incorporated into fundamental reference works and certified tables provided by the State Standards Commission of the USSR* as a result of measurements on thermal conductivity and thermal diffusivity for many refractory metals at temperatures up to the melting points, and on the thermodynamic and thermophysical characteristics of the alkali metals, methane-series freons, and dissociating nitrogen tetroxide.

Experiments have been performed with technically important concentrated salt solutions, fusible alloys, cast iron, and steels [2-4], which have given rise to tables of properties and to thermodynamic and phase diagrams, which are widely used for scientific and engineering purposes. The measurements have covered wide ranges in the state parameters and properties, so they are significant to the physics of gases and the condensed state as well as solution thermodynamics. The measurements have been used in an approximate theory of molecular scales for liquid metals and in a method of calculating the rate constants for reversible reactions (thermal diffusion) from data on the nonequilibrium speed of sound [3]; structural regularities have been identified and semiempirical formulas have been derived for forecasting the thermal parameters of the rare-earth elements [4] and for calculating the physical characteristics of magnetic liquids and the thermal conductivities of pressed metal powders (thermomechanical similarity in heterogeneous structures). The major scientific results include novel methods for examining properties: a modulation method of measuring thermal diffusivity by means of electron heating to 2500-3000 K, vibrational methods in viscosity measurement and phase analysis, a bithermal method of measuring solution-vapor equilibrium, a method for measuring the surface tension of a liquid metal at high temperatures, and a flow microcalorimeter for measuring the specific heats of gases.

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*Thermophysical Properties of Alkali Metals [in Russian], Izd. Standartov, Moscow (1970); Thermal Conductivities of Liquids and Gases [in Russian], Izd. Standartov, Moscow (1978); The Thermophysical Properties of Freons [in Russian], Parts I and II, Moscow (1982), etc.

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Research on the optical parameters and features of the thermal emission from substances involves electromagnetic and quantum theory, which defines the interactions of radiation with matter. The material and conditions (temperature and environment) vary widely, so experiment is primary. Measurements are made on integral and spectral radiation characteristics (degree of blackness, absorptivity and reflectivity, whether specular or hemispherical) at temperatures from those of liquid helium to 3000 K or more for wide ranges of materials. Particular interest attaches to measurements under conditions close to real ones (with chemical or other interactions with the environment and related structural changes). Spectral-reflectivity kinetics would provide a typical example of how chemical processes are involved for surface layers and related structural transformations, which has been examined for polycrystalline V1 graphite (Fig. 1, $\lambda = 1.725$ [5], O_2 flow speeds in m/sec: 1) 0.6, 2) 1.25; 3) 2.0). Important measurements have been made on emissivities at low temperatures. The calorimetric methods of measuring integral emissivity enable one to avoid the difficulties associated with measuring small fluxes emitted by bodies at cryogenic temperatures. The integral emission has been used to determine the phase-transition point for a niobium alloy at $T = 9.1$ K. Independent interest attaches to the emissivities of powder media at high temperatures. Measurements do not agree with calculations on the emissivities of powders containing metal oxides (Al_2O_3 and BeO) based on optical constants and complex refractive indices for single crystals, since these substances are polycrystalline under real conditions because they have passed through a melting stage. While the absorption parameter χ for single-crystal aluminum oxide varies stepwise near the melting point ($T_{mp} = 2320$), measurements with recrystallized aluminum oxide particles of diameter 50 ± 5 μm and concentration 0.022-0.234 g/cm³ [6] have given χ showing a monotone temperature dependence (Fig. 2).

Recently, there has been increased interest in the optical and thermophysical parameters of ultrafine particles. Measurements have been made on collective effects in two-dimensional systems of randomly disposed fine metal particles, where there is a nonlinear increase in the absorption coefficient and a shift in the plasma resonance as the particle concentration increases. These effects become appreciable when the distances between the particles are less than three times the diameter; the collective effect is dependent on the optical conductivity, which so far is not reflected in theoretical models.

Research on energy and mass transport covers a wide range of topics for gaseous, liquid, and multiphase media. Thermal conduction is the simplest form of energy transport in an immobile medium. Researches here largely amount to considering boundary-value problems for thermal conductivity in bodies of arbitrary shape, where various methods from mathematical physics are used. Particular attention has been given here to nonlinear treatments, which are required because the thermophysical parameters are dependent on temperature, as well as to nonlinearities in the boundary conditions (boundary conditions of Stefan—Boltzmann type), where computer methods are widely used.

Major aspects of heat-flux interaction have been considered [7] for conditions of limiting disequilibrium, where measurements showed anomalous temperatures (superheating) in surface layers for pure metals. For example, the superheating $K_+ = (\Delta T_e - \Delta T_c)/q$ is determined by the type of metal, the surface finish, the degree of blackness, and the structural perfection, where ΔT_e and ΔT_c are the experimental and calculated temperature differences across the thickness, while q is the input heat flux (radiation). Figure 3 shows the superheating in aluminum and zinc in relation to flux density, where curves 1-3 are for 99.995% Al correspondingly with electrochemical, mechanical, and electrochemical polishing with the specimen first forged, 4-6 represent Sn with electrochemical polishing, with curve 4 for 99.998% purity and curve 5 for 99.998% with forging, and 6 for 99.8%. Microstructure examination showed that there were dislocations in the layer at concentrations substantially exceeding those in the bulk. The theory of thermomechanics rules out dislocation multiplication in metals with the perturbations produced by heat fluxes of the above order. The theory of radiative heat transfer is required to analyze the heating for transparent or semitransparent media.

The theory of radiative heat transfer is based on the energy equation for electromagnetic wave transport in the ray approximation; here there has been a substantial effect from methods in astrophysical theory and then from neutron-transport physics. The theoretical approaches used in thermophysics are restricted to diffusion and quasidiffusion ones, spherical-harmonic ones (mainly the P_1 approximation), and integral equations or algebraic ones implied by them (zone methods). The integral equations are most widely used along with zone methods and forms of the average-flux method [8]. These integral equations can be solved for systems of

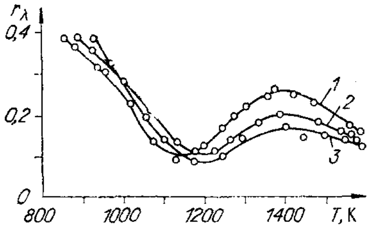

Fig. 1

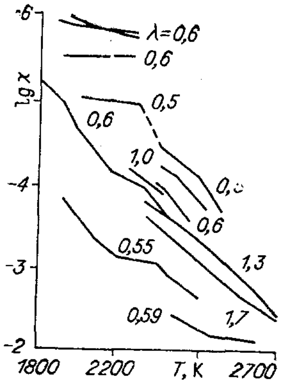

Fig. 2

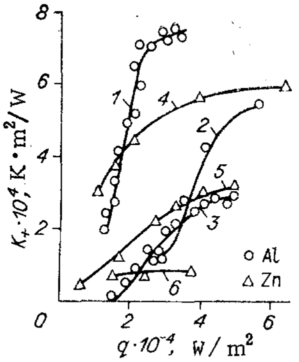

Fig. 3

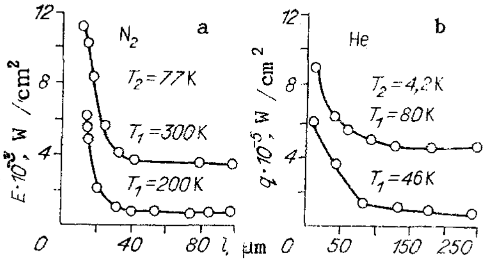

Fig. 4

classical configuration for a large range of practical purposes, but very often, one has to solve for one-dimensional transport in planar layers and unbounded cylinders filled with absorbing, emitting, and scattering media [8]. Classical solutions are used along with treatments giving the limits to the applicability. Experiment [9] shows that heat transfer between closely spaced metal plates (Fig. 4) does not obey the classical formulas if the Wien wavelength λ_w is comparable with the gap ($\ell \leq 3\lambda_w$, where $\ell T = 3b$, in which b = 0.2898 cm·K is the Wien constant), and instead it is necessary to use the theory of electromagnetic field fluctuations. Such researches have advanced the theory of multiple scattering for transfer in inhomogeneous media. For real conditions, this related to heat transfer in immobile conducting semitransparent media (radiative–conductive transfer), which is dealt with by experiment and in theory via numerical methods of solving nonlinear integrodifferential equations, which incorporate the spectral character of the transport, the temperature dependence of the thermophysical and optical parameters, etc. The main attention is given to radiation interactions, conduction, convection, and the effects of these on the temperature and heat-flux patterns [8].

Conjugate formulations of radiative–conductive transfer in optically inhomogeneous media are important for technological purposes; computer experiments show that the nonstationary temperature pattern in a two-layer system is nonmonotone because of the decisive role of radiation in optically inhomogeneous layers. In a liquid or gas, this nonmonotone feature can lead to loss of dynamic stability. Particular interest attaches to heating kinetics for semitransparent materials showing phase transitions. Such topics are of interest in relation to growing optical crystals.

Heat and mass transfer with free convection has many applications. In thermogravitational convection, studies have been made on the structure of the main laminar, transitional, and subsequent turbulent flows in planar layers with various orientations with respect to gravity, and also in horizontal layers with free surfaces (thermogravitational-capillary convection). The flow structure steadily becomes more complicated as the temperature difference between the boundaries of the horizontal layer increases or with increase in the dimensionless analog of the Rayleigh number ($Ra = \beta g/a\nu \, \Delta T H^3$). The heat flux is a piecewise-linear function of the temperature difference. Measurements have been made in the

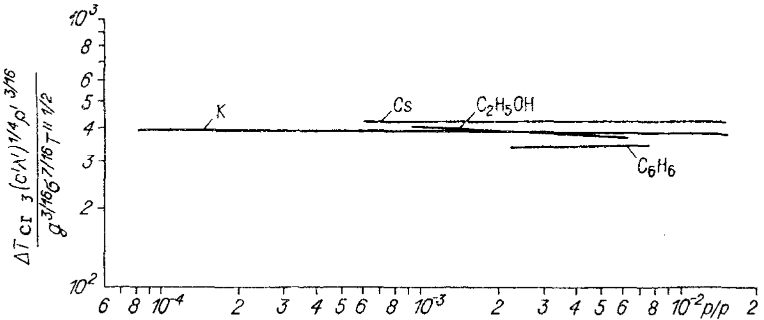

Fig. 5

range $1.8 \cdot 10^3 \leq Ra \leq 6 \cdot 10^4$ on the temperature and velocity patterns in the liquid cells, and formulas have been given for determining the heat transfer [10].

There are five types of instability of stationary and oscillatory types in the heat transfer in vertical and inclined layers of liquid as the inclination angle and Prandtl number Pr vary; turbulent convection sets in a vertical layer in accordance with $Ra_L = \beta g \Delta T L^3/a\nu \cong 5 \cdot 10^{10}$ and is characterized by a longitudinal temperature gradient at the center [11]. Identical structures are found for the turbulent boundary layers at a vertical isothermal wall in a large volume of liquid and at a vertical wall bounding a layer of liquid, while the local value of the heat-transfer coefficient is defined by the single relation $Nu_x = 0.108 Ra_x{}^{1/3}$.

Experiments have been performed on convective heat transfer in simulating Czochralski's method of growing crystals from the melt, and maps have been constructed for free, mixed, and forced convection for the regions where the different forms of flow occur.

Very complicated processes occur in liquids showing phase transitions such as boiling and condensation. There is at present no rigorous mathematical description for this. Experiments and semiempirical models are particularly important, as they indicate the main parameters and lead to relatively simple regularities.

Measurements have been made on boiling and heat-transfer crisis mechanisms for many liquids: alkali metals, water, organic, and cryogenic liquids [12-14]. A visualization method has been developed for examining metal boiling, and high-speed cinematography has been applied to opaque liquids. The main components are an x-ray equipment, electron-optical converter, and high-speed camera. This has provided the bubble detachment diameters, detachment frequencies, and bubble growth rates in alkali-metal boiling [15].

A new form of heat-transfer crisis has been observed in which a vapor film appears after single-phase convection without the occurrence of bubble boiling [12, 16]. There is a threshold superheating above which there is avalanche bubble formation in a metastable wall layer, with subsequent evaporation of that layer and film formation.

A cavitation model [17] gives a relation for the superheating for these conditions: $\Delta T^* = 3.8 \cdot 10^2 (T'')^{1/2} (c_p \lambda)^{-1/4} \sigma^{7/16} \rho^{-3/8} g^{3/16}$, which covers media differing in Prandtl number by several orders (Fig. 5). Hydrodynamic perturbations are decisive, which are emitted by the growing bubbles into the metastable layer and reduce the potential barriers hindering nucleation. The relationship is important also in that it defines the lower limit to the critical heat flux in unstable metal boiling.

Unstable vapor films are formed in the transitional boiling state and in unstable boiling because of threshold superheating (Fig. 6 shows the initial stage in the formation of an unstable film for ethanol). This gives formulas for the superheating of the transfer surface in the first and second crises, which describe the data for various liquid satisfactorily.

There is substantial heat transfer through the liquid for a metal boiling under critical conditions; incorporating this has extended the use of the hydrodynamic crisis theory to liquid metals [17]. A critical flux formula has been derived for subheated and saturated metallic and nonmetallic liquids, which describes the measurements to ±20%.

The critical flux q_{cr1} in boiling is described by Kutateladze's formula $K = [q_{cr1}/(r\sqrt{\rho''}\sqrt{g\sigma\Delta P})] = \text{const}$ proposed at the end of the 1940s, which follows from the assertion that the decisive part is played by hydrodynamics in the otherwise thermal process (here K = 16 for boiling liquids). In fact, the formula contains no thermal parameters, and thus is independent of the mode of light-phase bubble generation and applies for the entire class of two-phase (two-component) flows.

The gas entering a liquid through a microporous plate is used as a model for testing the decisive role of hydrodynamics in bubble-mode instability; systematic measurements have been made on the end to the bubble state under various conditions, and they have shown that there is a complete analogy between the crisis in bubble boiling and in plate bubbling (Fig. 7, curves 1 and 2). These bubbling studies have been made in relation to boiling, and the main postulates of the hydrodynamic predominance have been confirmed. The process is found to be of hydrogas-dynamic type, since the gravitational force and the dynamic head from the light phase are accompanied by viscous friction in the liquid and the acoustic pressure in the gaseous phase [18].

In research on vapor condensation on tube bundles, an important point concerns bulk condensation at supercooled drops and jets [19]. Figure 8 shows the temperature patterns for drops and jets of a condensate at T_c in the space between tubes h (R 12, $T'' = 60°C$, $\Delta T = 35°C$, 1) Re = 35; 2) 150; 3) 250, $T'' = 70°C$, $\Delta T = 50°C$; 4) 60; 5) 250). Each successive tube in the downward sequence receives liquid at a temperature equal or almost equal to the saturation temperature T". The initial part of a thermal boundary layer is formed at the surface of this tube, where the heat is transferred from the liquid to the wall by convection. The transfer is of mixed type, and the mean Nusselt number over the entire perimeter [20] is given by

$$\langle \mathrm{Nu}^*\rangle = (\langle \mathrm{Nu}_i^*\rangle x_i + \langle \mathrm{Nu}_c^*\rangle (\pi R - x_i))/\pi R,$$

where $\langle Nu_i^*\rangle$ is the mean value in the initial part of the thermal boundary layer and $\langle Nu_c^*\rangle$ is the Nusselt number on condensation in the region of laminar-wave flow. The measurements agree with the analytical solution for heat transfer in laminar flow, where a thermal boundary layer is formed [21].

Fig. 6

Numerous measurements have been made on heat transfer in the condensation of moving vapor around a horizontal cylinder in transverse flow; the friction at the vapor—film boundary is determined by the transverse flow.

Surface tension can accelerate heat transfer on condensation considerably in terms of the total surface for finned tubes; with the best distances between the fins, the heat transfer in bundles of finned tubes is only slightly dependent on the irrigation density.

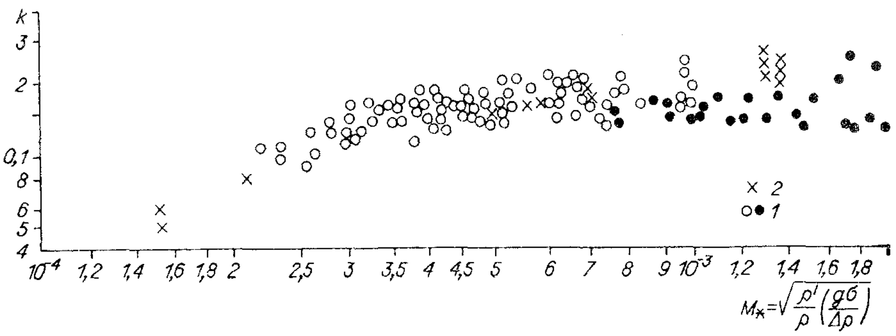

Fig. 7

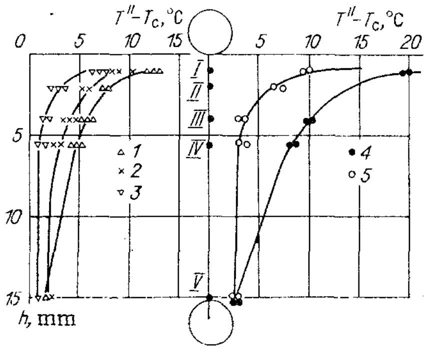

Fig. 8

Many aspects of heat and mass transfer in forced motion can be resolved by considering limiting or asymptotic situations, where the main features are apparent. Kutateladze [22] considered turbulent gas flow in a tube with rough walls and assumed that the viscous layer is disrupted by the inhomogeneities, which gave the relative friction law in the form $(c_f/c_{f_0})_{\mathrm{Re}} = [2/(\sqrt{\Psi}+1)]^2$, where $\Psi = T_W/T_0$ is the temperature factor. He subsequently showed that this formula is obeyed also for a gas in a smooth tube for $\mathrm{Re} \to \infty$. It has proved extremely fruitful to consider the limiting relative frictional and heat-transfer laws for turbulent boundary layers of vanishing viscosity, and it has led to the asymptotic theory of wall turbulence [23-37]. That theory provides approximate calculations on heat transfer and friction in gases with allowance for the compressibility, nonisothermal situation, inhomogeneity, surface permeability, physicochemical transformations, etc.

Studies on wall heat and mass transfer and flows [28] have led to the hypothesis that the thermal boundary layer is smeared out at an adiabatic wall [23, 24], where the asymptotic ratio of the energy loss thickness to the momentum loss one tends to a finite value $(\delta_T^{**}/\delta^{*}) \to 9$.

A general theory has been developed for gas injection and wall jets, and models have been proposed for the heat and mass transfer and friction for a wide range of flows involving gas injection, with various modes of organization, and for the flow conditions at adiabatic, nonadiabatic, and chemically reacting surfaces.

Measurements have been made on the effects of external turbulence on heat transfer and friction on permeable plates [29], as well as of flow history and injection intensity on turbulent heat transfer [30-32].

A boundary layer showing physicochemical transformations results in equations containing source terms, and consequently the dynamic equations are nonsimilar, as they belong to the

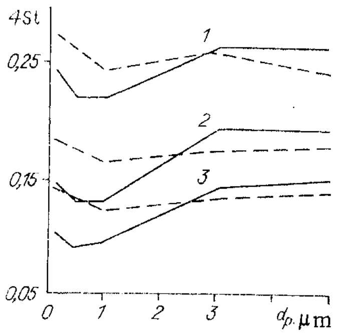

Fig. 9

class of ones difficult for analytical consideration. A hypothesis has been advanced on the triple Reynolds analogy, which applies to the diffusion approximation, and where the initial equations can be written in terms of the total enthalpies and the generalized concentrations subject to similar boundary conditions, which have given approximate methods. Integral formulas have been used to consider a wide class of flows involving heterogeneous combustion in the presence of flame fronts in the boundary layers [28, 33].

Radiative-convective heat transfer has many applications, but the main attention has been given to radiative transfer in laminar and turbulent boundary layers on permeable surfaces.

Numerical solutions can be given here, where the injection parameter can be varied for boundary layers with various absorption and scattering parameters, from which one can derive the most effective methods of thermal protection.

In particular, a gas at T = 1973 K flowing around a plate is most effectively dealt with as regards maintaining the minimum total heat flux $(\mathrm{St} = Q_w/[4\mathrm{Bo}(\Theta_w - 1)])$ by injecting a mixture of air with graphite particles having the optimum size range 0.5-1 μm (Fig. 9) [34]. Here the concentration is κ, while α is the particle size in the section of the laminar sublayer, with x/L = 0.03, κ = 0.2, 0.4, and 0.7 in lines 1-3, while the dashed lines are for air with Al_2O_3 and the solid ones are for air with graphite.

Considerable use is made of thermal plasmas having T > 3 × 10^3 K generated in arcs. There are complicated coupled phenomena in the discharge channel and at the electrodes, with the channel geometry influencing the thermal and electrodynamic processes, as also do the electrode material, the gas flow mode, etc., so it is now impossible to formulate precise analytical studies. Similarity-theory methods are widely used. Although the processes in a plasmotron are complicated, one needs to use only a relatively small number of similarity criteria [35].

There are two states in the gas dynamics and heat transfer in a cylindrical channel containing a longitudinally flushed arc, namely stabilized and unstabilized. In the unstabilized (turbulent) state, the discharge is not axisymmetric and has a complicated branched optical structure. The conducting zone in a developed flow is localized near the axis on account of the turbulence [36].

The thermal efficiency of an arc plasmotron is raised by gas injection (discrete injection). The performance from injection is defined by $\Theta' = (q_c - q_{cs})/q_c$ in a cylindrical channel, where q_c and q_{cs} are the densities of the convective heat flux without and with the injection. The empirical relation $\Theta' = (1 + 0.24\,K)^{-0.8}(1 + K^2)^{-0.14}$ applies closely, where $K = z\mathrm{Re}_s^{-0.25}/m_s s$, z is the coordinate along the flow, $m_s = \frac{\rho_s u_s}{\rho_0 u_0}$ is the injection parameter, s is slot width, and $\mathrm{Re}_s = \frac{\rho_s u_s}{\mu_0}$ is Reynolds number. The measurements are closely described by this (Fig. 10, where the points are from experiment, the solid line is from the general relation, and the dashed line is the performance on a plate). The performance in a cylindrical channel is less than that for a flat plate; the gas is injected at an angle to the main flow to improve this [37]. The core of an arc burning under stabilized conditions at hundreds of amperes (T = (12-18)·10^3 K, radius (3-10)·10^{-3} m) gives up almost all its energy by radiation over a wide spectrum, including the vacuum ultraviolet. The latter is efficiently absorbed by the comparatively cold gas, which makes an appreciable contribution to the thermal state.

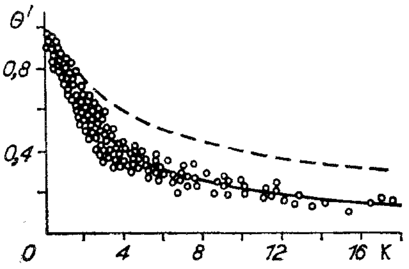

Fig. 10

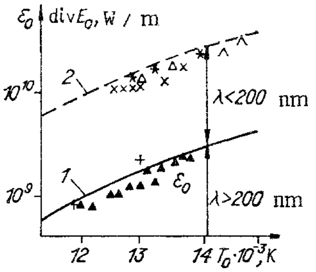

Fig. 11

Figure 11 confirms this from the emissivity ε_0 and radiation-vector divergence div E_0 as functions of arc plasma temperature for air and nitrogen (curves 1 and 2 are from theory, while the points are from experiment); ε_0 characterizes the volume emission at $\lambda > 200$ nm, while div E_0 covers a wider spectral range, including $\lambda < 200$ nm. About 80% of the emission is absorbed in the ultraviolet, while 9% for the air arc is absorbed by the wall, while the rest of the energy goes to heat the gas entering the axial region. The convection–radiation interaction under stabilized conditions leads to constant thermal and electrical characteristics. In a turbulent arc, the radiation and convection are accompanied at sufficiently high currents by interaction between the radiation and the turbulence, which simulation [38] shows as reducing the turbulent thermal conductivity.

Physical hydrodynamics has developed from researches on the thermophysics of moving media, particularly in power-producing technologies; there is a need here to upgrade fundamental concepts on the heat-transfer mechanisms for turbulent flows. An electronic stroboscope has been applied to hydrodynamic measurements, as have microthermocouples, which have yielded new information on the viscous sublayer structure and related momentum and heat-transfer mechanisms directly at the wall [39, 40]. Synchronous measurements on the turbulent velocity and temperature fluctuations have shown that there are extensive hydrodynamic excursions and penetration, particularly of the flow in the viscous sublayer, and these are very probably accompanied by similar thermal events [41].

Particular interest attaches to the behavior of a turbulent flow on adding a polymer [42]. Such researches with small amounts of polymer have shown that the resistance is reduced, while there is a substantial increase in the intermediate turbulent-flow region, with an increase in thermal resistance. The polymers reduce the extent of the transverse velocity fluctuations and the anisotropy in the turbulent vortices, and high-frequency fluctuations are damped out. The characteristic time scale for the coherent structures increases with the resistance-reduction effect.

As plants increase in power and heat loading, it becomes more important to make reliable calculations on heat transfer under transient or emergency conditions. Nonstationary processes may be due to time variations in the power production, coolant flow, inlet temperature or all together [43].

Computerized equipment has been used to measure wall friction in different states of flow; the deviations from quasistationary values increase with the rate of change in the flow velocity, and those in weak polymer solutions are much larger than in water. Statistical studies have been made on the fluctuations in temperature and heat-transfer coefficient for nonstationary heat production in channel walls [44].

Rheological measurements indicate that there is a class of media showing linear fluidity laws, for which methods have been devised for calculating friction and heat transfer in circular and planar channels subject to various boundary conditions and with allowance for the temperature dependence of the rheological parameters and possible liquid slip at the wall [44].

A phenomenological approach has been proposed to describe nonequilibrium flows of nonlinearly viscoelastic liquids. Calculations and experiments have been made on laminar flows under various conditions: stationary, transitional, or pulsating. Detailed studies have been made on pulsating and oscillating polymer-solution flows in tubes. Critical conditions have been defined for the spontaneous occurrence at unstable flow of such solutions in channels, which is an effect undesirable in extrusion.

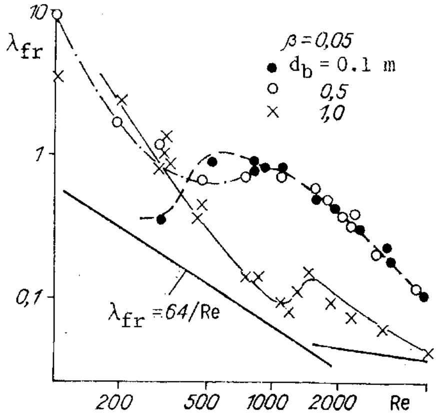

Fig. 12

Gas—liquid and vapor—liquid media are widely used in power engineering, chemical engineering, oil and gas transport, etc.; research on hydrodynamics and wave processes has recently given rise to a special area; the wave dynamics of gas-liquid systems.

Hydrodynamic researches have been concerned with the flow of such mixtures in pipes. Measurements have been made on wall friction and the components of the pressure difference under various states of flow for a horizontal two-phase system: from stratified to plug and dispersed annular. The resistance coefficient is described satisfactorily by calculation methods given by Armand and Lockhart-Martinelli, apart from the range of low reduced velocities [45].

Measurements have been made on the fluctuation spectral densities for the frictional stresses in vertical and horizontal two-phase flows, and an objective method has been devised for identifying the state [46]. Nominal flow characteristics have been measured for the plug state at the moments when liquid plugs and gas sections pass through, and it has been shown that the wall friction in the liquid makes the main contribution to the resistance [47, 48]. Measurements on wall friction and velocity profiles in ascending two-phase flows have shown that there is a state of anomalously high friction in the bubble made for Reynolds numbers of 2000 and more. The friction coefficient λ_{fr} in this range may exceed that in a one-phase flow by a large factor even for small gas contents β (Fig. 12, where d_b is bubble diameter) [49, 50].

Measurements have been made on the fluctuating velocity components for the liquid in a two-phase flow. There is asymmetry in these components at the center of the pipe, in contrast to the one-phase flow. The Reynolds stresses are different from zero even at subcritical Reynolds numbers, which is due to the extensive turbulence produced by the relative motion of the gas phase [51, 52].

There are substantial differences in hydrodynamic characteristics between rising and descending two-phase flows in vertical tubes. An ascending flow has asymmetry in the friction distribution over the perimeter due to the uneven gas content distribution in the wall layer. A descending flow is symmetrical and the gas concentrates at the center of the tube, and sometimes turbulent pulsations in the wall region are suppressed [53, 54]. The purpose of these studies has been to construct the theory of such flows for use in chemical engineering, power engineering, and pipeline transport.

Measurements have been made on hydrodynamics and mass transfer for liquid films, and numerous experiments have been performed on laminar and turbulent flows. The wave speeds and amplitudes have been determined, and the friction at the wall has been measured in laminar-wave and turbulent modes of flow [55, 56]. Studies have been made on the effects of waves on the mass transfer through the free surface. The theoretical wave profiles [57] describe the observed laminar-wave states closely (Fig. 13). The small-perturbation stability of the waves has been examined.

A theoretical model has been proposed for the mass transfer accentuated by waves; it agrees qualitatively with experiment [58-60]. A theory has been constructed for waves of small and medium amplitudes in a liquid containing bubbles of vapor and gas, which incorporates all the main features of two-phase media: high nonlinearity, dissipation, dispersion in the

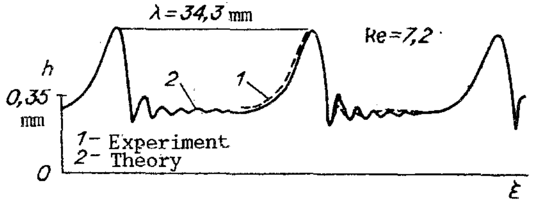

Fig. 13

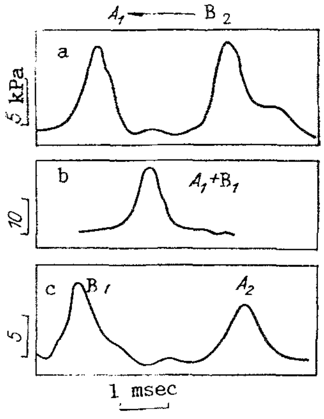

Fig. 14

speed of sound, and heat and mass transfer between phases. The theory is based on canonical approximation due to Burgers, Korteweg, and de Vries (BKdV) and to Boussinesque, as well as on the BKdV relaxation equation and the Klein–Gordon equation. A two-wave approach has also been devised for analyzing the behavior of waves with initially steep fronts. The procedure for deriving the model equations is equivalent to that for deriving similarity criteria in fitting curves to measurements and setting up the calculation methods.

New effects have been observed and explained in the wave dynamics of media containing bubbles: the marked effects of the gas parameters on the wave evolution (thermal relaxation for shock waves), acoustic precursors in the propagation of waves with steep fronts, and the considerable increase in shock-wave intensity in vapor–liquid media under certain conditions.

Various wave states in gas–liquid media have been observed and explained: shock waves having oscillating monotone and transitional (relaxation) profiles, singular waves (solitons), and wave packets. Measurements have been made on shock-wave interaction and the passage of solitons one through another (Fig. 14). There is a direct relationship between wave structure and the dynamics of vapor and gas inclusions. In a vapor–liquid medium, there are two essentially different asymptotic states for wave processes: thermal and inertial.

Wave dynamics have been discussed for energy-bearing pressure perturbations in plug structure for gas–liquid and vapor–liquid flows. A quasicontinuum model has given canonical equations whose solutions apply for wavelengths comparable with the plug dimension. Measurements have been compared with the theory to elucidate all the observed characteristic wave states in terms of the similarity criteria, where it is possible to determine the existence limits [57].

Shock waves occur near the critical liquid–vapor point, which is related to second-order phase transitions and affects numerous physical properties, as in liquid helium, superconductors, and liquids at ordinary and high temperatures.

Tensile shock waves occur because of the anomalous reduction in the speed of sound as the pressure rises; an equation has been derived for the structure of such waves [61]. Other research on the wave dynamics of two-phase media has been associated with problems in power engineering, chemical engineering, cryogenics, and the oil industry.

Measurements have been made on spiral gas injection; centrifugal forces have a marked effect on the transport, and they can modify the flow radically [62, 63]. A theory has been proposed that defines the action of the mass forces on the pulsating motion [64], which agrees well with measurements for various types of such flow.

Extensive studies have been made on the hydrodynamics of rotating flows in pipes, cyclones, vortex chambers, and toroidal vortices. A theory has been devised for centrifugal spraying, which is free from unsound hypotheses or empirical rules. A simple inexplicit formula has been obtained for the relative radius ξ of the axial cavity $\Lambda^2 = [(1 - \xi^2)^2 + 2\xi^2(1 - \xi^2)\ln \xi]/2\xi^2$, where Λ is a quantity determined by the geometry.

Stability in rotating flows has been examined, and measurements have been made on the mechanics of viscous vortex flows (spiral flows in circular tubes with permeable or impermeable walls). A theory has been set up for concentrated dispersal systems, which predicts metastability there [65-67].

A maximum-stability principle has been proposed for averaged turbulent flows, which enables one to calculate the empirical wall turbulence constants. A theory of structural turbulence has been derived, which is based on the corpuscular character of the structures arising at random instants and randomly placed and oriented in space [68].

Cryohydrodynamics is becoming a distinct speciality; means are available for systematic research on heat transfer and hydrodynamics in free or forced convection, as well as in rotating systems containing cryogenic liquids. Results have been obtained on the effects of cryostat rotation on boiling heat transfer; visualization has provided a demonstration that Coriolis forces affect the hydrodynamics and heat transfer on boiling in a rotating system [69].

Measurements have been made on induced convection in large volumes, particularly the effects on the critical heat flux on stepped heat production at thin cylindrical heaters in liquid nitrogen. A theoretical relationship has been proposed for the minimal heat flux for film boiling [70].

A series of studies has been performed on thermal pulses in superfluid helium; small-amplitude perturbation propagation is described satisfactorily by the nonlinear theory of second sound in He II. As the pulse intensity increases, deviations from this theory appear because the temperature increases in the wall layers and a vapor film is formed. It has been shown that these phenomena are related to quantum vortices in He II [72].

Low-density gas dynamics is a fundamental section of physical mechanics that arose during the early years of the Institute of Thermal Physics. A suite of large-scale vacuum systems has been built with extensive functions and diagnosis techniques [72] (Fig. 15), which radically extends physical researches here [73]. Interest in relaxation in the translational degrees of freedom for molecules has led to the development of a method for separating gas or isotope mixtures based on spatial separation by mass and cross section on injection into a light-gas flow [74].

Researches have been conducted for many years on supersonic gas jets entering media with low counterpressure (including vacuum) [75, 76]. The general structure has been examined, along with the conditions for gas-dynamic similarity, and the effects of vacuum, and efficient numerical methods have been devised [77]. Gas-dynamic models have been set up for structured flows, which enable one to use jets as tools for researching nonequilibrium processes (rotational and vibrational relaxation, emission, and condensation).

Measurements on rotational energy exchange for diatomic molecules have given the rotational relaxation rate constant for nitrogen in the previously inaccessible low-temperature range (down to 10 K) for the entire set of active rotational levels. Research on adiabatic nucleation, flow clustering, and cluster features has made it possible to produce a gas state by nucleation in disequilibrium on the internal degrees of freedom; similarity laws have been determined for nonequilibrium condensation of molecular gases on adiabatic expansion in jets; limits have been set to the particle sizes for which the surface energy and the activity in molecular-energy exchange begin to differ from the bulk values: and studies have been made on the interaction of low-energy electrons with clusters of light inorganic molecules (adhesion, ionization, and dissociation). In research of cluster interactions with surfaces, it has proved possible to determine the effects from the phase states of the clusters and electrification conditions at the surface [78-80].

There is an important applied result from research on jets and nonequilibrium processes in the creation of new jet vacuum-pumping facilities: oil-free cold diffusion pumps and energy-saving vacuum and high-vacuum ones.

Nanosecond laser diagnosis has been used in local measurements on supersonic flows with nucleated turbulence; the turbulent modes represent an organic component of such a flow and have dimensions corresponding to a Knudsen number of 0.01. Here it has been possible to research turbulent-energy generation and dissipation at the molecular level.

The main lines of research at the Thermophysics Institute define the general trends in the field; in particular, there has been a substantial extension in the types of working body and the applications of them. Increased significance attaches to microphysical studies on the properties of matter. There has also been increased emphasis on classification and generalization based on similarity theory.

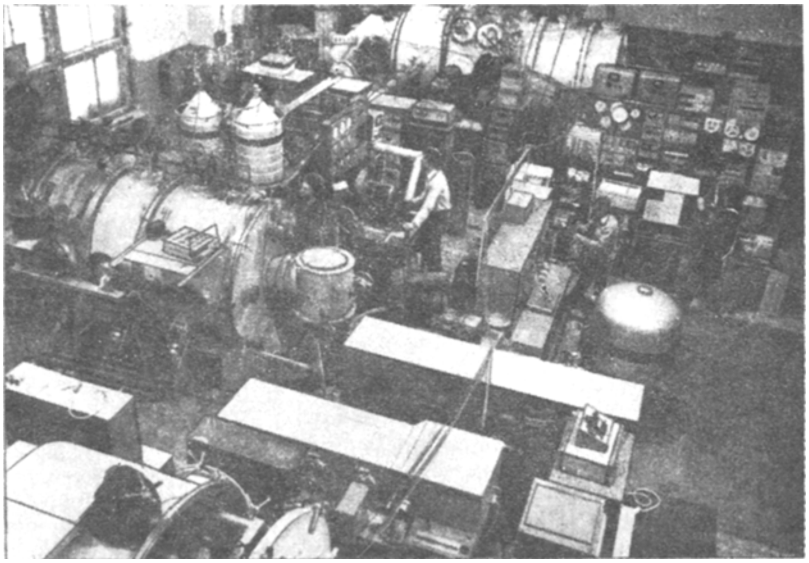

Fig. 15

In thermal conductivity, interest continues to increase in boundary-value problems containing nonlinear energy equations and boundary conditions, as well as inverse problems, conjugate formulations for problems involving phase transitions, and the problems of thermal shock, where one has to consider the effects of thermal factors on the properties of materials. Treatments have been given for semitransparent materials, in which there is bulk absorption of thermal radiation. A trend has also appeared for correlating the structures of materials with processes occurring in them (thermal protection materials and optical crystals).

Advances are expected in the theory and in research methods for heat transfer in media involving bulk absorption, emission, and scattering in two-dimensional and three-dimensional systems showing selective interaction between radiation and matter under nonequilibrium conditions. The interest in applications has extended considerably, since the field covers not only technological and power-engineering problems but also thermal protection from intense radiation.

Measurements on heat transfer in boiling and condensing media have passed through a long stage of data accumulation, but there is still no clear-cut conception of the mechanism responsible for the boiling crisis in forced flow in heat transfer near the critical point or in condensation associated with reactions and other phenomena. It is now important to formulate experiments involving local-characteristic measurement on two-phase flow capable of improving the models and giving a theory for heat transfer in the liquid—vapor transition region.

There has also been extensive research on free convection, which is decisive in many technological processes and natural phenomena: crystal growth, microgravity, and liquid media. In convective transfer there has been a shift in interest from integral characteristics to internal local mechanisms. Current developments provide an insight into the mechanisms responsible for turbulence, and also the interactions between vortices on different scales. The effects of rheological parameters on transfer in liquids are related to establishing connections between macroscopic properties and microstructure.

There are prospects for research on the detailed structure of vortex flows, and in the determination of turbulent transport suppression and acceleration under mass forces. There is also interest in the structures of turbulence and in the structural theory of wall layers.

There have been rapid developments in the wave dynamics of gas—liquid and vapor—liquid media. The researches are based on nonlinear wave dynamics and new methods of incorporating phase interaction. The high compressibility in such a two-phase system is accompanied by heat and mass transfer, dissipation, and dispersion in the speed of sound. Reliable description of these complicated processes must be based on the fullest use of wave concepts in combination with suitable experiments. Particular attention is given to turbulence in detachment zones in systems where the turbulence level is comparable with the characteristic flow speed, as well as to mathematical and physical simulation of infiltration at high rates and heat transfer in porous media in relation to oil extraction and chemical engineering.

Experiments on heat transfer and hydrodynamics with free or forced convection in cryogenic liquids are extremely laborious, but comprehensive studies have been made in relation to the physical properties of the working bodies, which have shown that additional thermophysical experiments are needed. Particular interest will attach to future research on nonstationary heat transfer in He II, which is a quantum liquid with unusual flow and thermal-perturbation propagation mechanisms.

A suite of large-scale vacuum systems gives good scope for fundamental research in molecular physics and gas dynamics. Research is in hand on the physical properties of ultrafine particles (clusters) in relation to fundamental aspects of the structure of matter, which throws light on topics in materials science, power engineering (combustion), ecology, etc.

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DEFORMED SOLID MECHANICS AT THE SIBERIAN BRANCH, ACADEMY OF SCIENCES OF THE USSR

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From the creation of the Siberian Branch in 1957 in determining the main directions for development of mechanics its organizers have devoted considerable attention to deformed solid mechanics. This was connected both with the solution of a series of important dynamic strength problems and with general problems of developing engineering. It turned out that from the first plan for developing this direction at the Institute of Theoretical and Applied Mechanics (ITAM) (Academician S. A. Khristianovich) a new plan was born, i.e., development as a basis for the whole subject of an experimental section of deformed solid mechanics at the Institute of Hydrodynamics (IG) (Academician Yu. N. Rabotnov). The plan for studying solid mechanics realized in this section was creation of experimental equipment based on the newest technology, systematic experimental study of modern materials, phenomenological description and its comparison with experimental data, creation and development of resolving strength problems and the stability of structural elements taking account of irreversible strains, and finally introduction of these methods into design bureau.

Forms of organization were determined for theoretical and experimental studies of deformed solid mechanics in institutes of the Siberian Branch of the Academy of Sciences of the USSR (SO AN SSSR), a department was organized at Novosibirsk State University (NSU), as well as work of the Council for Defending Dissertations in this subject at the Presidium of the SO AN SSSR. In these decisions it is possible to see the breadth of organizational questions, i.e., from strengthening and developing scientific contacts with the main schools in Moscow, Leningrad, Kiev, and with large groups of applied subjects, to systems for training groups of highly qualified specialists. It is necessary to say that not all of this was possible: some important specialists did not arrive for the work: theoreticians and experimentors did not develop the test design base with sufficient quickness. Nonetheless, at the present time thirty years after the creation of the SO AN SSSR, it is possible to note that now in the Siberian Branch the groups of different institutes are developing forcefully almost all of the main important themes of this scientific subject. It is necessary to refer to the following:

— creation of mathematical models for the deformation of solid deformed bodies including a study of irreversible strains (plasticity, creep) and failure; creation of a set of test installations making it possible to study the main connections between stresses and strains with different types of static and dynamic loads equipped with automatic control and recording;

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