BOOK REVIEWS

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PROGRESS IN HEAT AND MASS TRANSFER, VOL. 2*

Reviewed by Z. P. Shul'man

The second volume of collected papers in the monograph series Progress in Heat and Mass Transfer, issued as a supplement to the International Journal of Heat and Mass Transfer, has been published. The collection is devoted to the 65th birthday of Professor E. R. G. Eckert, the outstanding contemporary thermophysicist and aerodynamicist.

The preface, the official part of the collection, is devoted to honoring the celebrant. An address signed by the editors gives a laconic biography of Professor Eckert, describing his fruitful scientific, pedagogical, and engineering activities, and noting his great contribution to world science.

Professor Eckert has gained a great and well-deserved reputation. The introductory part of the collection contains, along with the welcoming address, a list of the services, awards, and honorary titles of the celebrant, and also the greetings of A. V. Lykov, director of the Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR.

The second part of the collection is opened by the paper of Hadji-Sheich and Sparrow (USA) devoted to the use of the Monte Carlo method for solving problems of heat radiation and for estimating the errors of the method. The authors were able to formulate a universal probability distribution for the wavelengths and direction of propagation of photon beams in radiation which is independent of the radiation characteristics of the surfaces and of the temperature level. The programming of such a universal distribution, will greatly reduce the expenditure of effort and time in preparing calculations by the Monte Carlo method. The problem of radiant heat transfer between two plane-parallel plates is examined as an illustration. Nonuniversal distributions borrowed from the literature are also used for comparison. It is shown that the use of the universal distribution can provide any preassigned accuracy of the calculations.

Much space in the collection is devoted to the problem of natural convection (eight papers). Although this is a classical field of physics, there is still a lack of experimental data and consequently most of the articles are devoted to experimental investigations of natural convection.

The results of measuring gravitational natural convection in the gap between two silvered, parallel, vertical plates of finite size (150 × 100 mm) are reported in Nowotny's paper (USA). The dimensionless width of the gap (its ratio to the height of the plate) was varied inthe experiments from 0.0165 to 0.0624. The plates were placed in a large container (600 × 500 × 900 mm) filled with a 0.35% aqueous solution of silver nitrate the optical refraction of which differed by only 0.5% from the refraction of pure water. By means of measurements involving a Mach–Zehnder interferometer it was possible to establish the interesting result that in very narrow gaps effect of lifting forces on the character of heat transfer is weak. It was found that in this case the local Nusselt numbers and the temperature distributions in the flow region are in good agreement with the solutions of the Gratz problem for forced motion in the hydrodynamic stabilization section. It is only with considerable spacing of the plates (of the order of 12 mm) that the

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temperature profiles and local heat fluxes reflect the specific characteristics of free convection (maximum on the velocity profile and dependence on the Grashof number), as observed for a single plate.

The paper of Pollard and Carlson is devoted to an experimental investigation of the effect of deflectable plane fins (movable flaps) on the nonsteady-state natural convection of a liquid in a bounded volume and on temperature stratification. The ratio of the height L of the vessel to its width W (distance between opposite heated walls), the spatial position of the flaps (horizontal and at a 45° angle up and down), and the length of the flaps were varied. It was found that:

a) with a constant number of fins they have a certain optimal size for each fixed value of L/W;

b) for fixed dimensions (length l) of the fins they have an optimal number which, however, depends not only on L/W but also on l/W and the ratio of the heat fluxes of the wall and bottom of the vessel q_b/q_w;

c) horizontal fins have maximum efficiency with respect to heat transfer;

d) the degree of stratification depends on q_b/q_w and decreases with approach to $q_b/q_w = 1$ (the opposite trend is found with a further increase of q_b/q_w);

e) the effectiveness of fins (the ability to prevent stratification) decreases with time, reaching an asymptotic value;

f) in all cases the system reaches a quasi-steady-state regime 5 min after applying the thermal effect, at a rate which depends on the intensity of heating the walls of the vessel and its dimensions;

g) the local heat fluxes measured on the vertical walls of the vessel in the case of a turbulent regime of motion proved to be slightly greater than that theoretically predicted for a vertical plate located in an unbounded medium.

The problem of free convection in a thermally stratified medium is analyzed also in Eichhorn's interesting paper (USA). The problem of determining steady-state velocity and temperature fields in the boundary layer of an isothermal vertical plate located in an undisturbed stratified medium is solved. In the medium there is a linear distribution of temperature T_∞ increasing upward. On the leading edge of the plate its temperature exceeds T_∞ so that the thermal head $\Theta(x, 0) = T_w - T_\infty$ along the plate changes according to the law

$$\Theta(x,\ 0) = \Theta_0\left(1 - \frac{ax}{\Theta_0}\right).$$

Here $\Theta_0 = T_w(0, 0) - T_\infty$ is the initial thermal head in section x = 0; $a = dT_\infty/dx$ is the longitudinal (vertical) temperature gradient in the medium.

In this formulation the thermal problem is analogous to the statement of the classical problem of a hydrodynamic boundary layer for a flow passing longitudinally around a plate with the velocity of the external potential flow of the "one-slope profile" type diminishing linearly on passing downward along the stream; this problem was solved by Howarth numerically by series expansion in self-preserving variables. The same method and operative procedures, based on the well-known self-preserving variables of the boundary layer of free convection of an isothermal vertical plate, are used in the paper. This procedure produces an infinite sequence of linear (except one) ordinary differential equations for universal coefficient-functions (thermal φ_i and dynamic f_i) of series for the stream function of a viscous flow and for local thermal head. The values of φ_i and f_i for Prandtl numbers from 0.1 to 100 and i = 0, i, 2 are obtained by the numerical method. The local values of viscous stress and heat fluxes thus calculated are compared with the results of interferometric measurements obtained by Eckert and Carlson in a vertical slot formed by two unbounded parallel plates. The agreement was good on the greater part of the slot (more than 3/4 of its height).

Quite interesting data and the results of interferometric investigation of thermal convection in a horizontal layer of air are given in the paper of Goldstein and Chi (USA). A layer of air between two isothermal horizontal plates was examined. One of them (lower) had a temperature $T_1 > T_2$ (temperature of the upper plate). The Rayleigh numbers were continuously changed during the experiment from 10^3 to 10^8

so as to determine their critical values corresponding to the start of periodic cellular motion and subsequent loss of its stability with transition to turbulent mixing. According to the authors' measurements, for $Ra \simeq 1783 \pm 60$ a regular cellular laminar motion of a periodic nature stationary in time and space arises in the gap with a ratio of the width to the height of the cell from 1.9 to 2.5. This result agrees well with the theoretical value Ra = 1708 known from the literature. Up to this critical value in the gap there is a regime of molecular heat conduction with a linear temperature profile. In the range $6 \cdot 10^5 < Ra < 1.2 \cdot 10^8$ developed turbulent motion was observed, for which the experimental data were generalized by the empirical formula

$$Nu = 0.123 Ra^{0.294},$$

which agrees well with Silweston's know correlation, but the profile of the statistically averaged temperatures differed noticeably from the theoretical predictions.

The paper of Lykov, Berkovskii, and Fertman (USSR) discusses the new phenomenon of free thermal convection in a horizontal slot due to inhomogeneous heating from above. On the basis of a general analysis of the system of hydrostatic equations in a horizontal prismatic cavity, the authors established that mechanical equilibrium is possible only in the steady-state case of isothermality of both horizontal faces and the same linear law of variation of temperature on all vertical faces. In this case the density is determined as a linear function of temperature.

As an example the authors consider the problem of the occurrence of natural convection in a closed horizontal rectangular cavity, all vertical faces of which are isothermal; a stepwise temperature distribution is given on the upper face. Half of its surface (from the middle to the edge) is maintained at about the same temperature level as the entire lower face. The other half of the face has a higher temperature. In this case a laminar circulating motion localized over the width of the transitional region of the temperature profile on the upper wall should arise spontaneously in the cavity.

Also an analysis was conducted of the equations of equilibrium of a liquid in the case when the system is subjected to a uniaxial magnetic field the strength vector at which is oriented vertically. In this case disturbance of mechanical equilibrium can be due to changes of both the temperature and magnetic fields.

The authors performed experiments with two horizontal bronze plates (205 × 700 mm). The vertical walls of the chamber were made of organic glass (ends) and optical glass (front and rear walls). Distilled water with light-scattering additives (aluminum powder with a 0.23% concentration) was placed in the gap (3 mm). A gas laser served as the light source. A constant temperature of 22°C was maintained on the lower plate. One half of the upper plate had the same temperature and the other half was 10.5° higher.

As a result, visualized patterns were obtained of the circulating motions near the upper plate, which were localized in the region of transition from one temperature level to the other. Experiments conducted by the same method with heating from below gave the well-known pattern of cellular convection.

The paper of Sing, Birkeback, and Drake (USA) was devoted to the little-investigated problem of laminar natural convection from a horizontal surface. A finite isothermal plate, placed with the heated side facing down and placed in a less-heated medium (or placed with the cold side facing upward), was investigated.

It is known that natural convection does not occur in the case of an unbounded plane horizontal surface. Movement of heated masses of the medium near the edges is characteristic for finite plates. Passing around the edges and corners, these lighter masses float upward and entrain the remaining part of the heated medium, thereby creating a longitudinal flow near the surface. As a consequence of this, vertical currents of the medium being ejected should arise normal to the wall. On the basis of this pattern of three-dimensional steady motion, the authors use the scheme of a three-dimensional boundary layer of finite thickness for solving the problem. At first a system of integral conditions of the dynamic and thermal layers is derived and parabolic temperature and velocity profiles (two components) are selected.

The partial differential equation obtained for the layer thickness δ is solved by the Ritz–Galerkin methods under the condition that δ decreases from its maximum in the center of the plate to zero at its edges. As a result simple formulas were obtained for the Nusselt number as applied to a square plate, round disk, and infinite band in the form:

$$\mathrm{Nu} = \frac{\alpha L}{\lambda} = Af(x,\ y)\,(\mathrm{Gr}\cdot\mathrm{Pr})^{1/5},$$

where L is the characteristic dimension (half-width of the plate, radius of the disk); f (x, y) is a known function of the coordinates of the surface of the plate, inversely proportional to the boundary-layer thickness; and A is a constant, incorporating the temperature and dimensions of the surface, and the density, viscosity, temperature, thermal diffusivity, and compressibility of the medium.

A comparison of the calculations with Wagner's experimental data and with the experiments of Cadamby and Drake showed excellent agreement. The divergences in most cases do not exceed 2%.

The section of the collection devoted to natural convection ends with the extensive experimental investigation of Knowles and Gebhart (USA). The problem of the stability of a laminary boundary layer of natural convection on a vertical electrically heated plate, 0.01 mm thick, 51 mm wide, and 324 mm high, is considered. The medium was silicone oil (hexamethyldisiloxane) with Prandtl number 7.7 and kinematic viscosity 0.68 cS (at 30°C). The development both of natural perturbations of velocity and temperature and those created specially was studied. An electromagnetic vibrator served for this purpose. Its frequency was regulated smoothly in the range $8 \cdot 10^{-3}$-20 Hz and the amplitude could be varied continuously from zero to 0.125 mm. The vibrations (harmonic oscillations) were imparted to a thin strip, 3.2 mm high and 127 mm wide, located in the boundary layer normal to the heated surface of the plate in the horizontal plane.

Two hot-wire anemometers with a heated platinum wire (5μ in diameter) were used for measuring the velocity fields of the principal and perturbed motion. Observations and measurements of the temperature fields were accomplished by a Mach–Zehnder interferometer. The measurement results are compared with the linearized theory of small perturbations developed by the authors.

Treatment of the experimental data for various values of the heat flux and frequency and amplitude of vibrations showed that, in the overwhelming majority of experiments, the exponent in the dimensionless dependence of heat transfer on the Grashof number varied between −0.40 and −0.54 and averaged −0.45. The authors attribute this divergence to the dependence of the wave propagation velocity on the longitudinal coordinate which was neglected in treating the data. With this correction the agreement between the experiment and linearized theory is good. Thus the possibility of using the linearized theory of natural convection for media with large Prandtl numbers was proved.

Another important result of the measurements consists in the establishment of a relation between losses of stability and the characteristic points of the velocity and temperature profiles. Previously it had been generally assumed that loss of flow stability begins near the point of inflection of the velocity profile. However, it was established in these experiments, that at high Prandtl numbers the perturbations of temperature and velocity reach their maximum values near the maximum velocity of the unperturbed flow. Two appendices to the article contain calculations of the sensitivity of the hot-wire anemometer, sensor and interferometer. The first problem is quite important, since the measured flow velocity is extremely small (of the order of 10^{-3} m/sec) and the heated sensor immersed in the flow creates additional natural convection. The relationship between the displacement of the interference fringes and the corresponding temperature difference in the silicone oil is derived in the second appendix.

This extensive and interesting paper contains a detailed description of the experimental technique, apparatus, and instruments, and also gives a thorough interpretation of the measurement results.

Important and exceptionally interesting results of an experimental investigation of convective heat transfer at quite large Prandtl numbers are contained in Zoengen's fundamental paper (USA). The experiments were carried out with vertical plates and circular cylinders (horizontal and vertical) placed in a high-viscosity polymeric liquid, Polybutene N-300 with a Prandtl number of the order of 10^6. Heretofore data on heat transfer during free and forced convection were absent from the literature for such media. Both steady-state heat transfer processes and transitional processes arising upon sudden delivery (removal) of a heat flux to the surface of a streamlined body were studied in Zoengen's experiment. The thermophysical characteristics of the working liquid in the −60°C to +20°C temperature range changed as follows: viscosity by a factor of 280 and the heat conductivity, specific heat, and thermal diffusivity changed by 6%, 11%, and 7%, respectively, i.e., remained practically constant.

The experiments of natural convection were carried out both on vertical surfaces (high heat-capacity cylinder and low heat-capacity plate) and on horizontal metal cylinders and fine wires. Forced convection was studied on horizontal round wires.

In view of the fundamental character of Zoengen's experiments we will dwell in greater detail on them.

I. Natural Convection

A. Vertical copper cylinders in the form of hollow tubes, 37 mm in diameter, 150 mm long, and wall thickness of 7 mm, were immersed into a 650 mm diam. vessel filled with the working liquid. A tubular, electrically heated element which provided isothermal conditions on the outer surface of the cylinder was positioned centrally inside the body. The specimen was joined coaxially to two unheated plastic end cylinders identical with the specimen in diameter and length. Thermocouples were arranged parallel to the generatrix of this composite cylinder at various distances from its outside surface.

B. The vertical plane plate was a fiberglass sheet, 0.9 mm thick, 450 mm high, and 250 mm wide, on both sides of which were glued three 0.05 mm thick foil strips of identical dimensions. Thermocouples were attached on the middle strip at various distances from the lower end of the plate. The strips were heated by an electrical current. Constancy of the heat fluxes over the entire surface of the plate was thereby secured. The heat-transfer coefficients for the cylinders and plate were calculated by two methods: on the basis of the power of the electrical current and wall–medium temperature difference, and also on the basis of the temperature of the body surface in the flow and the temperature gradient on it. The latter was found by differentiating the temperature profile measured by the thermocouples.

The development of the boundary layer and the temporal change of its thickness in the nonsteady-state process were investigated by the shadow method with a streak camera. The velocity fields in the transitional regime of natural convection were determined by means of a special visualization technique, to which end a string of fine aluminum powder was created in the liquid normal to the vertically heated surface of the cylinder or plate. Upon occurrence of natural convective motion, the particles were entrained by the fluid. Photography of their displacements at specific fixed time intervals permitted a calculation of the velocities of the liquid medium at various distances from the wall, i.e., the velocity profile.

C. The horizontal electrically heated cylinders had diameters of 6.35 mm and 0.8 mm and length of 15 cm. They were fastened on a U-shaped plastic holder.

II. Forced Convection

The experiments were carried out with an electrically heated wire, 0.5 mm in diameter and 150 mm long, stretched between the ends of a U-shaped holder. By means of a special electromechanical device the model was moved vertically (upward) through a quiescent medium at a constant rate that varied from experiment to experiment in the range (17-170) mm/sec.

A. In the experiments with the vertical cylinders the main parameter was the specific heat flux delivered to the surface, the constancy of which was secured during each experiment. Measurements began under isothermal conditions in the absence of a temperature gradient between the body and medium, i.e., $\Delta T = T_b - T_m = 0$. Then a given heat flux q was delivered and measurements were taken of the temperatures of the wall T_b and adjacent layers of the liquid, and also of the thickness of the thermal boundary layer δ_b as a function of time τ. The local characteristics of motion and heat transfer α were determined for the vertically arranged bodies, and for the horizontal bodies only the averaged characters over the entire cylindrical surface were determined. The experiments covered the ranges of variation of the parameters

$$q = (0.29 - 3.7)\cdot 10^3 \text{ W/m}^2;\ \Delta T = 0-78\,^\circ\text{C};\ \Pr = (0.3-9.7)\cdot 10^5;$$

$$\text{Gr} = 0.1-600;\ \text{Ra} = \text{Gr}\cdot\Pr = (0.28-175)\cdot 10^5.$$

The entire process of development of natural convection near a vertical circular cylinder, as the measurements showed, could be divided into the following three periods.

1. The initial period is characterized by the absence of molecular convective heat transfer. The isotherms in the liquid are arranged parallel to the generatrix and the temperature field in the medium is the same as in the problem of heat conduction of a semibounded bar.

2. The transitional period is the period during which convective motion of a creeping character develops. This means that the motion is formed only by lifting, Archimedean buoyant forces and by the viscosity of the medium – the inertial forces make an insignificant contribution to the dynamic balance. Whilst the boundary layer is being established, convection gradually overlaps heat conduction and narrows the region of its effect. A steady boundary layer of free convection is formed at the end of the transitional period. However before the steady state, characterized by the quantity δ_{st}, is reached, the boundary-layer thickness "overlaps" δ_{st} and only after a certain time does it thin to this value.

3. In the steady-state period, motion, heat transfer, temperature fields, and other characteristics of the process depend on time and obey the law $Nu = 0.47\ Ra^{1/4}$. The phenomenon of "overlapping" of the steady-state thickness of the boundary layer was observed on both vertical bodies: cylinder and plate. It usually occurs on the lower third of the height of the body and only for magnitudes of q exceeding certain values. Another interesting and important result of the experiment with vertical bodies is that, despite "overlapping" of the boundary-layer thickness, the temporal change of the heat-transfer coefficient is monotonic during all three periods. The most careful measurements did not reveal a minimum on the curve $\alpha(\tau)$.

Thus it was confirmed that the classical relation $Nu = C\,(Gr \cdot Pr)^{1/4}$ is valid in the range of Prandtl numbers from 0.5 (gases) to 10^6 upon a change of the Rayleigh number from 10^4 to 10^8. Only the constant C changes. For large Prandtl numbers its value is close to 0.56. Contrary to theoretical predictions, transverse curvature of the body did not affect heat-transfer characteristics, although the ratio of the boundary-layer thickness to the radius of the cylinder exceeded 1.3.

B. For a vertical plate with an initial isothermal wall the program covered the following ranges of variation of the experimental parameters:

$$q = (3-19)\cdot 10^2\ \mathrm{W/m^2};\ \Delta T = 0-50\,^\circ\mathrm{C};\ Ra = (0.01-30)\cdot 10^6;\ Pr = (0.5-4)\cdot 10^5.$$

The local characteristics were measured in sections located 5 and 20 cm above the lower edge of the plate. In the transitional period the temperature of the isothermal wall varied according to a law close to the Ellingworth relation

$$T_b - T_m = \frac{q\sqrt{\pi a \tau}}{2\lambda}$$

(a, λ are the thermal diffusivity and heat conductivity of the medium, respectively), obtained from the solution of the problem of nonsteady-state heat conduction. When steady-state convection is reached the wall temperature does not depend on time, but varies over the height of the plate. The temperature profile in the first (conductive) period, as measurements showed, is approximated nicely by a cubical parabola

$$\frac{T_b - T}{T_b - T_m} = \left(1 - \frac{y}{\delta}\right)^3,\ \text{where } \delta \neq \sqrt{12 a \tau},$$

obtained earlier by Siegel from the solution of the problem of the thermal boundary layer of a uniformly heated vertical plate (q = const). In this period α was independent of the heat flux of the wall and the plate height. The heat-transfer coefficient depends then only on time and the transport properties (a and λ).

C. Natural convection from horizontal bodies was measured on electrically heated cylinders (nickel) with a diameter of 6.3 mm and nickel and platinum wires with a diameter of 0.8 mm. However, the data for the platinum wires have a large scatter of the points on the graph which, in the author's opinion, is explained by the catalytic effect of platinum on the liquid.

The measurements were taken in the ranges $q = (7\text{-}70)\cdot 10^2\ \mathrm{W/m^2}$; $Pr = (1\text{-}6)\cdot 10^5$; $Ra = (4\text{-}200)\cdot 10^2$. In these experiments the boundary-layer thickness greatly exceeded the radius of the cylinder and consequently the classical scheme of the boundary layer is inapplicable. The paper contains a series of photographs of the shadow pattern of successive development of the thermal boundary layer around the 6.3 mm diameter cylinder for two values of the heat flux $q_1 = 2\ \mathrm{kW/m^2}$ and $q_2 = 5.4\ \mathrm{kW/m^2}$. In both cases soon after electrical heating and thermal boundary layer increases symmetrically relative to the heated surface of the body. Gradually the symmetry is disturbed under the effect of Archimedean buoyant forces, and the layer acquires the form of a vertical ovaloid. In the case of low-intensity heat delivery a vertical wake gradually forms in the upper part of the ovaloid. In the case of large heat deliveries the upper part of the ovaloid breaks suddenly and a free convection flow occurs. In this case the thickness of the thermal boundary layer rapidly diminishes after formation of the wake, which gives rise to the aforementioned "overlapping" effect of the thickness of the steady-state thermal boundary layer. Individual shadow patterns in the paper illustrate the behavior of the thermal boundary layer upon sudden removal of electrical heating and subsequent cooling of the model body. In this case the wake and upper of the thermal boundary layer progressively degenerate, whereas the lower semicylindrical part persists for some time. The data given in the article on measurement of the temporal change of the thickness of the thermal boundary layer (in the plane of a horizontal section through the diameter of the cylinder) and of the heat-transfer coefficient averaged over the entire surface of the cylinder $\bar{\alpha}$ indicate an appreciable "overlapping" effect δ_t and accordingly a nonmonotonic shape of the curve $\alpha(\tau)$. The "overlapping" effect in the given case is much higher than for vertical bodies. Its intensity increases with an increase of the heat flux and diameter of the body. Thus, for d = 6.35 mm and q = 0.55 W/cm^2 the difference between δ_{tmax} and δ_{tlim} is about 40%, whereas for d = 0.8 mm and q = 104 W/cm^2 the value of δ_t increases with time monotonically and smoothly, approaching its aymptotic value. Simultaneously the intensity of heat transfer averaged over the surface $\bar{\alpha}$, decreasing, passes through the minimum and then reaches a steady-state value. The depth of the "valley" on the curve $\bar{\alpha}(\tau)$ is not so great relatively as the peak on the curve $\delta_t(\tau)$. For example, with a 25% "overlapping" effect of the layer thickness only an 8% decrease of $\bar{\alpha}$ is attained.

The author's experimental data for horizontal cylinders in the range $10^{-1} \le \mathrm{Ra} \le 2 \cdot 10^2$ agree well with the "one-fourth" law

$$\overline{\mathrm{Nu}} = 1.75\mathrm{Ra}^{1/4}, \qquad (*)$$

whereas according to the Langmuir theory of a frozen, purely heat-conducting film the exponents should be half as much. Until recently it was considered that Ra = 10^4 was the critical value of transition from a region of pure heat conduction to convection. However, as it turned out, the value of Ra_{cr} is much lower (by five decimal orders), since, according to the data of Zoengen's experiments, heat transfer to Ra = 10^{-1} is determined by the convective law (*) rather than by the heat conductivity of the film. The main causes of such divergences between experiment and Langmuir's theory can be considered the presence of motions inside the film and their gradual increase during the entire transitional period, which are not accounted for by this theory. The purpose was to study the regularities of steady-state heat transfer of circular cylinders past which flow transversely fluids with high Prandtl numbers ($\sim 10^6$) at small Re < 10^{-1}. It was of interest to reveal the possibility of describing the characteristics of heat transfer by empirical formulas used for large and moderate values of the Reynolds number. It was necessary to determine the role of natural convection and its effect on forced heat transfer. The experiments were conducted on a horizontal 0.5 mm diameter nickel wire with coinciding direction of natural and forced convection (motion of the body upward). The ranges of measuring the parameters of the experiment were : q = (3.3-280) kW/m^2; ΔT = 8-130°C, relative velocity of the body (1.7-17) cm/sec; Re = $(5 \cdot 10^{-4}$-$1.3 \cdot 10^{-1})$; Ra = $(1.5 \cdot 10^{-2}$-$2)$; Gr = $(3.8 \cdot 10^{-8}$-$10^{-4})$. All experimental points were positioned on the curve

$$\overline{\mathrm{Nu}} = 0.82\mathrm{Re}^{0.28}\mathrm{Pr}^{0.31}. \qquad (**)$$

As in the experiments on natural convection, the physical properties in formula (**) were referred to the arithmetic mean temperature of the boundary layer (film). According to Grayner's latest experiments, natural convection plays an ever-greater role with decrease of the Reynolds number of the heated horizontal wire. From these experiments follow different values of Nu when the wire is blown from below upward and from the top downward. This difference, due to the opposite direction of forced and natural convection, disappears when Re < 10^{-2}. Below this limit the value of Nu is determined only by the process of natural convection and retains its values irrespective of the value of Re and direction of blowing.

Zoengen's experiments did not confirm this conclusion, since relation (**) remained valid to Reynolds numbers of the order of 10^{-4}. Thus for fluids with large Reynolds numbers the region of degeneration of forced convection is shifted by another 3-4 decimal orders below Grayner's predicted limit $\mathrm{Re}_{cr} = 10^{-2}$. As the analysis showed, this shift is due to the contribution of the Grashof number rather than to the effect of the Rayleigh number. The paper has many illustrations.

The paper of Griguhl and Straub (West Germany) is devoted to the temperature dependence of surface tension σ near the critical state. On the basis of a thermodynamic analysis the authors establish a new idealized $\sigma-T$ diagram for the temperature range $T = 0-T_{cr}$ in the form

$$\frac{du}{dT} = -T\frac{d^2\sigma}{dT^2}. \qquad (***)$$

Here $u = TS + \sigma$ is the internal energy referred to a unit interphase surface; T is the thermodynamic (absolute) temperature and T_{cr} is the critical temperature; S is the specific entropy (referred to a unit interphase surface).

Relation (***) leads to an important result, namely, within the $0-T_{cr}$ temperature range there should exist on the $\sigma-T$ curve a point of inflection (correspondingly the maximum of the $u-T$ curve). In this region relation (***) coincides with the classical formulas of Eotvos (linear dependence) and van der Waals (parabola of the m-th order with $m = 1.5$). The latter is valid also for the near-critical region. Experiments with CO_2 and CF_3Cl were set up to check relation (***). The experiments were conducted with three calibrated glass capillaries with radii of 50, 770, and 1450μ placed in a special cuvette, where the pressure and temperature could be created and kept at prescribed constant values. The height of the capillary rise was recorded by a cathetometer. The experiments confirmed relation (***) in the near-critical region. Their results were approximated by a parabolic-type empirical formula but with an exponent m different from van der Waals'. A considerable temperature dependence of m was found for associated fluids (water).

The collection contains five further papers on the problem of surface cooling. The first of them, belonging to Keiker, Bye, and Whitlow, is devoted to the problem of calculating turbulent jets in problems of film cooling. The authors discuss the possibility of using the Spalding–Pathankar method for calculating the characteristics of the friction and heat and mass transfer of such flows.

The following goals are set up:

1. By generalizing the experimental data in the literature, to elucidate the problem of the similarity of the profiles of the mixing length l_1 and effective Prandtl (Pr) and Schmidt (Sc) parameters for various ratios of the discharge velocity from the slot u_s to the velocity of the external flow u_e and different distances from the slot x.

2. To calculate the characteristics of film cooling and especially its effectiveness by using the simplest formulations of the aforementioned profiles and the Spalding–Pathankar method of calculation.

   Exceptionally abundant, diverse, and fresh data are collected and analyzed in the paper. The following conclusions are made on the basis of the authors' calculations and their comparison with the measurements of other investigators:

   a) In the general case there is no similarity of the profiles l_1, Pr_{ef}, and Sc_{ef} for different abscissas, x, in a near-wall turbulent jet. At the same time a trend of approximate similarity of profiles is noted for $u_s/u_e > 1$.

   b) A value of the effective Schmidt number equal to 0.5 ± 0.2 can be taken for the outer part of turbulent boundary layer (above the maximum on the velocity profile).

   c) The Spalding–Pathankar method of calculation gives acceptable predictions of the effectiveness of film jet cooling and of the corresponding velocity, temperature, and concentration profiles in wide ranges of variation of the density of the medium and ratios u_s/u_e. In this case the calculation includes an uncomplicated composite Prandtl model of the mixing length ($l_1 = 0.435\ y_1$ for the wall part of the jet and $l_1 = 0.09\ y_1$ for its outer region) and linear changes of the effective Prandtl and Schmidt numbers across the layer (from 1.75 on the wall to 0.5 on the outer boundary).

The short note of Simon, Hartnett, and Lew (USA) proposes new correlations of the characteristics of a laminar boundary layer of air and nonair media around a plane surface during transpiration. The authors generalized the literature and their own data on friction, heat transfer, and coefficient of restitution for various pairs of gases (CO_2-N_2, CO_2-H_2, CO_2-CO_2, H_2-N_2, H_2-CO_2, H_2-H_2, H_2-air, CO_2-air, Xe $-$air, He$-$air, Ar$-$air, I_2-air), Mach numbers (0, 3, 4, 6, 8, 12), temperatures of the external flow

(218, 297, 555, 1110, 1666°K), ratios of the temperatures of the wall and medium (0.5, 0.25, 1, 1.1, 2, 3, 6), ratios of molecular masses of the medium and injected gas (1/22-22). It is shown on this basis that the relative characteristics of surface friction C_f/C_{f0}, heat transfer St/St_0, and restitution r/r_0 can be represented by their own universal relation if generalized parameters are used

$$\left(\frac{M_1+M_2}{2M_1}\right)^{1/2}\left(\frac{M_2}{M_1}\right) f_w/\sqrt{C^*} \text{ — for friction;}$$

$$\left(\frac{M_2}{M_1}\right)^{1/3} f_w/\sqrt{C^*} \text{ — for heat transfer;}$$

$$\left(\frac{M_1+M_2}{2M_1}\right)^{5/4}\left(\frac{M_1}{M_2}\right)^{1/5} f_w/\sqrt{C^*} \text{ — for coefficient of restitution.}$$

Here M_2, M_1 are the molecular masses of the medium and injected gas, respectively: $f_w = (\rho_w v_w/\rho_\infty u_\infty) \cdot \sqrt{Re_{x,\infty}}$ is the injection parameter; $C^* = (\rho_2^* \mu_2^*)/(\rho_\infty \mu_\infty)$ is the Chapman–Rubezin parameter (the asterisk denotes assignment to characteristic conditions).

The index "0" pertains to data for an impermeable wall, which are calculated by Eckert's method. The graphs and tables in the paper confirm the acceptable accuracy of the correlations in the ranges of variation of the physical conditions indicated above.

The paper of Chen and Ostrakh (USA) analyzes the analytical solution of the problem of ablation melting of two-dimensional and axisymmetric blunt bodies with consideration of the effect of mass forces on the hydrodynamics and heat transfer of a liquid film.

The authors proceed from an associated mathematical formulation of equations on an incompressible boundary layer on both sides of the interface between the gas and liquid film. The solutions join on the indicated interface. All physical properties, except the viscosity of the liquid phase, are taken to be constant. The temperature dependence of viscosity is expressed by a decreasing (hyperbolic type) exponential function. The temperatures of the external potential flow and inside the solid melting body are considered constant. The analytical solution is reduced to finite formulas thanks to the use of the assumption of the existence of an equilibrium form of the nose part of the melting body. It is postulated on the basis of the experiments of one of the authors that the nose part of the blunt body after an initial period of melting acquires a plane geometry of the plate type located normal to the incident flow. This form thereafter remains unchanged. Thus it is possible to use in calculations the previously known methods of solution and the results for the boundary layer of plane axisymmetric critical points. On this basis simple relations are obtained which associate the temperature of the liquid–gas interphase surface $T_{i.s}$ and specific rate of melting V with given characteristics and parameters in the external free flow. The quantity $T_{i.s}$ proved to be independent of the Reynolds number of the gas and decreased with an increase of the Peclet number of the liquid film and with an increase of the absolute value of the exponent in the temperature dependence of viscosity. Here the value of $T_{i.s}$ is 16% lower for the two-dimensional problem than for the axisymmetric problem, other conditions being equal. The rate of melting increases as the square root of the external flow velocity. The value of V, just as $T_{i.s}$, is 16% lower for the transversely circumfluous cylinder than for a sphere.

The mass forces, as the calculation showed, have a noticeable effect on the characteristics of the melting process. In the case of decelerated motion they increase the rate of melting and lower the temperature of the interphase surface. The opposite trend occurs for accelerated motion, although the quantitative aspect of this effect is different in both cases. For the same geometries of the bodies and conditions in the external flow at the same absolute magnitude of the mass forces the contribution of deceleration is twice higher than the contribution of acceleration. The authors determined the so-called limiting deceleration above which an equilibrium plane configuration of the nose of a melting body is impossible.

The paper of Sustry and Hartnett (USA) is devoted to an analytical investigation of the role and effect of an unheated preenclosed section on friction and heat transfer of a longitudinally isothermal porous plate situated in a gas flow with transpiration of a gas identical to the ambient medium through its wall. The mathematical formulation of equations of an incompressible laminary boundary layer in Mises–Prandtl variables is used for the calculations. Here the initial velocity profile from the self-preserving Blasius problem and temperature jump are assigned at the inlet of the porous section. The system of differential equations of continuity, momentum, and thermal energy is integrated numerically with the use of a rectangular network and Ames–Crandall implict finite-difference scheme. For the particular case of the absence of injection the authors' calculated values of $St/\sqrt{Re_x}$ are compared with Eckert's exact solutions for an impermeable plate. The divergences for $x/x_0 = 2$ are 7.5% and increase with a further increase of x/x_0 (x_0, x are the length of the initial impermeable, unheated section and the moving coordinate, reckoned from the leading edge of the plate). For a nonzero injection parameter the calculated dependence of St/St_0 and C_f/C_{f0} on f_W is compared with the analytical dependence of Sparrow and Starr for the case $x_0 = 0$, i.e., $x/x_0 = \infty$ and of Luganelli ($x/x_0 = 2$). In the latter case the divergences are rather considerable and increase with an increase of the intensity of injection (St_0 and C_{f0} are the local values of the Stanton number and friction coefficient for an impermeable wall). As a result it is shown that the initial length noticeably affects the characteristics of heat transfer and friction. Thus, for $x/x_0 = 2$ and $f_W = 1$ its neglect leads to an almost 30% underestimation of the effectiveness of porous cooling. For friction under the same conditions the corresponding value is 40%. However, the effect of a preenclosed impermeable, unheated section weakens with increase of x (at a fixed value of x_0) and becomes negligibly small for $x/x_0 = 10$.

The paper of Koch, Price, and Coloni (USA) solves the problem of nonsteady-state heat and mass transfer from a wall with two movable boundaries. It is concerned with the physical situation characteristic for modern methods of heat protection of surfaces subjected to large thermal actions (reentry of a satellite or rocket into the dense layer of the atmosphere, thermally stressed nozzles and combustion chambers, etc.). The physical scheme of the problem is as follows: the plate (cylinder wall, sphere) consists of a heat-insulated layer of a low heat-conducting material (base). A layer of porous refractory material (tungsten) is in close contact with the base. The pores are filled with a solid, good heat-conducting material (copper). The exposed surface of this composite layer, starting at a certain instant, is acted upon by a powerful heat flux q (of the order of 10^4 kW/m^2) due to aerodynamic heating, thermal radiation, etc. As a consequence of this the temperature of the body increases to the melting point of the metal enclosed in the pores. The interface of the liquid and solid phases gradually sinks deeper into the wall. At some instant (this depends on q and the pressure of the ambient medium) the boiling point is reached and the liquid phase begins to evaporate – a gaseous interlayer forms around the body, creating an additional blocking effect of heat protection. The liquid–gas interface moves toward the base. The problem is to determine the temporal dependence of the temperature of the body, and also the effectiveness of heat protection as functions of the thermophysical and thermodynamic properties, porosity, and permeability of the skeleton, dimensions of the layers, curvature of the wall, pressure of the external medium, and density of the heat flux acting on the wall. The problem is formulated as a system of equations of one-dimensional heat conductivity of solid, liquid, and gaseous layers. The diffusion of vapors into the ambient medium is ignored. The effect of mass transfer on heat transfer is taken into account by using in the calculation the appropriate relations, both empirical and those based on the theory of a transpiration boundary layer. In addition, the Clapeyron relation associating the vapor pressure on the interface with its equilibrium temperature, and also Darcy's percolation formula are used. The system is integrated numerically according to the implicit finite-difference scheme, which is similar to that proposed earlier by Eckert for problems with one moving phase interface.

A quite interesting numerical example is given at the end of the paper. An external heat flux q is assigned as varying in time according to an inverted parabola (increase from zero to $2 \cdot 10^4$ kW/m^2 during the first 12 sec and a drop to zero during the next 12 sec). The external pressure at first increases linearly from zero to 100 atm during the first 16 sec and then remains constant. The results of the calculation are presented in a graphic form. It is shown that the porosity of tungsten plays an exceptionally large role in maintaining the wall temperature below the allowable limit (the melting point of tungsten). The greater the porosity, the more effective the heat production and the lower the temperature of the porous layer and base. This trend is more favorable in the case of a plane wall and least favorable for a spherical surface. A cylindrical wall occupies an intermediate position. New data are given relative to the effect of porosity and curvature of the wall on the rate of penetration of the gas–liquid interface into the body. For 80% porosity only 30% of the copper is evaporated by the time the effect of the external heat fluxes ceases (24 sec) and 70% remains in the liquid phase. For 20% porosity 90% of the copper is evaporated within only 16 sec. This factor is manifested more strongly in the case of spherical geometry and more weakly for a plate.

The short paper of Kestin and Wood (USA) discusses the problem of intensifying heat transfer at the front point of a cylinder in a transverse flow by increasing the degree of turbulence of the incident flow. The paper is of an interpretive nature and relies on Kestin's earlier experiments. A circular cylinder of

Plexiglas, d = 76.6 mm, wrapped in a single layer of thin carbon paper and immersed into a suspension of aluminum paint in machine oil was used in the experiments. For 20 min the cylinder was in a transverse flow with a 2% degree of turbulence at Re = 10^5. In this case the boundary layer near the front part of the cylinder remained laminar. Striated bands of the eroded coating with a distance between the tips of the stria equal to λ, regularly repeating along the axis of the cylinder, formed on both sides of the critical line on its surface. It was shown that the value of λ depends on the Reynolds number, decreasing with its increase. The rate of this decrease in turn depends on the degree of turbulence of the incident flow. On this basis the authors construct their hypothesis relative to the causes of the increased (by 50%) heat transfer at the critical front point of the cylinder in comparison with the theoretical predictions. In their opinion, such intensification is explained by elongation of the vortex filaments in the incident flow. To check the hypothesis, additional experiments were carried out with the use of two hot-wire anemometers with heated wires. Both sensors, submerged to about the middle of the boundary-layer thickness, were located on the same generatrix 60° from the front critical line. One sensor remained stationary and other moved along the generatrix. Two-point correlations of the velocity fluctuations were recorded. The graph of the change of the correlation along the length of the cylinder for Re = 10^5 and 2% degree of turbulence has the form of a sequence of quasi-periodic fluctuations with a relative value λ/d, which is exactly the same as in the case of the aforementioned erosion experiments. The authors consider this fact a confirmation of the theory of elongation of the vortex filaments.

The detailed paper of Spaulding (England) presents calculations of the characteristic length of turbulence for some shear flows of the nonwall type (free jets, wakes, mixing layers). The author attempts to explain why free turbulent flows realized in a quiescent medium of such different geometry as a plane mixing layer and plane axisymmetric and radial jets have about the same angle of expansion at such different values of the Prandtl mixing length. The calculation is based on the Kolmogoroff–Prandtl turbulence model and the Rott differential equation for a longitudinal change of the characteristic length of a turbulent flow. To these relations are added another three differential equations (of the type of integral boundary-layer conditions) for momentum and the kinetic energy of average and fluctuating motions. Their integration is done under the assumption $k \ll u^2/2$ (k is the kinetic energy per unit mass of the fluid; u is the velocity deficiency in the boundary layer, i.e., the difference of velocities on the axis of the jet and on its outer boundary in the ambient medium). On this basis analytical expressions for the angle of expansion $(1/\delta)$, each containing four constants (l is the characteristic length of turbulence, δ is the local width of the jet), are obtained for each type of jet. It is interesting that the analytical form of all these expressions proved to be the same. They differ from one another by the constant multipliers whose absolute values are close to one another (deviations within 10%). Estimates of the order of magnitudes of the aforementioned four constants are derived in conclusion.

The collection also contains the paper of Lykov, Shul'man, Puris, and Zhdanovich (USSR) devoted to an experimental investigation of rheodynamics and convective mass transfer in the case of external flow of non-Newtonian media past bodies. Configurations most important in a hydrodynamic respect were selected for the experiments:

a) a streamlined body without separation – a plate in a longitudinal flow without static pressure gradients;

b) a poorly streamlined body – a circular cylinder in a transverse flow of a non-Newtonian medium.

The experiments were carried out by the same method with the use of electrochemiluminescence, i.e., combination of luminophor molecules in an electrolyte. The paper is a continuation of previously published investigations which contained a description of the measurement method and rotating-type experimental device, and also the analytical solution of the problem of dynamic and diffusion boundary layers of a plate with a preenclosed passive section with an exponential equation of the rheological state.

The following were varied in the experiments: lengths of the preenclosed passive section h_0 and active mass-transfer surface L (h_0 = 0, 7, 23, and 51 mm, i.e., $h_0/(h_0 + L)$ = 0, 0.064, 0.18, and 0.33), weight concentration of the aqueous solution of sodium carboxymethylcellulose (c_{NaCMC} = 0, 0.1, 0.25, 0.5, 0.75, 1, and 1.5%), velocity on the incident flow on the body (V_∞ = (10-50) cm/sec). The working solutions had well-defined anomalous properties – up to c_{NaCMC} = 1% a nonlinear viscosity prevailed, and at higher concentrations elastic properties became influential. Another noteworthy feature of these solutions was the marked nonlinearity and nonmonotonic character of the concentration dependence of the coefficient of diffusion of low-molecular ions through the solution. Up to $c_{NaCMC} = 0.5\%$ the value of D increases steeply and then passes through a maximum and drops progressively. Such a shape of the D(c) curve is characteristic of the majority of polymeric solutions and creates a specific character of the convective mass-transfer processes in them. In the experiments with the plate the local values of the the density of the diffusion flow onto its active surface in the range of generalized Reynolds numbers $Re = \rho U_\infty^{2-n} L^n/k = 10^2\text{-}5 \cdot 10^4$ (n and k are rheological parameters of the exponential equation) were measured.

The data obtained are presented in a generalized form. They are compared with the authors' analytical formulas, and for c = 0 (i.e., n = 1) with the well-known Levich–Meiman relation. For all values of c, h_0, Re, $Pe = U_\infty L/D$ the agreement of theory with experiment proved to be good. Only for c > 1% did the experimental data systematically deviate from the theoretical curve. In the authors' opinion, this divergence is due to viscoelastic effects which were not taken into account in their theory. The abscissa of the transition of the laminar boundary layer to turbulent is determined from the sharp jog on the log j_W–log x curves. Such experimental data were obtained for the first time. The paper discusses various aspects of the problem of the transition of a laminar boundary layer to turbulent and the empirical inequality

$$10^2 \leqslant Re_{cr} \leqslant 5 \cdot 10^4,$$

is derived, which differs markedly from the transition condition proposed earlier by Skelland on the basis of theoretical considerations, namely

$$3 \cdot 10^5 < \left[\frac{0.332}{A(n)}\right]^2 Re_{cr}^{\frac{2}{1+n}} < 3 \cdot 10^6; \; 0.332 \leqslant A(n) \leqslant 0.8.$$

The paper presents the relation $Re_{cr}(n)$ obtained from the experiments, which has a sharply decreasing character with an increase of non-Newtonian pseudoplastic properties, i.e., the value of Re_{cr} decreases steeply with decrease of n.

The experiments with transverse flow past circular cylinders were carried out in the range of variation of generalized Reynolds numbers $Re = 10^4\text{-}5 \cdot 10$. The local values of the j-flows on the circular contour of the cylinder were obtained in them just as for the plate. It was found that for fixed body dimensions and constant ambient velocity the intensity of mass transfer of all sections of the cylindrical surfaces in the flow decreases with an increase of the pseudoplastic properties of the solution, i.e., with a decrease of n. This degeneration is especially substantial for the front and stern regions. Thus, as the non-Newtonian properties increase the surface of the cylinder becomes increasingly more equally accessible for ion diffusion toward it. It was also established that, with an increase of the non-Newtonian and visocoelastic properties of the solutions, the separation line no longer has a conservative position and is strongly displaced downstream at Reynolds numbers for which in a non-Newtonian fluid with the same effective viscosity the azimuth of the position of separation is stationary and amounts to about 83°. The paper presents a series of photographic flow patterns confirming the conclusions made on the basis of the local j-measurements. Thus, for c = 1% the azimuth of separation is displaced to a 155° angle. In addition to the phenomenon of delaying separation noted by the authors, the effect of polymer additives on the character of motion in the stern region of the body and in the wake behind it was also studied. It is shown that such additives, first, greatly weaken and smooth out the eddy structure in this region and, second, noticeably affect the parameters of the Karman vortex street, primarily the frequency of shedding of the vortices. The paper gives the pertinent relations and their intepretation. The motion picture frame convincingly confirms the authors' conclusion that the vortices are formed as a result of rolling-up of the shed sheet in the wake and not as a result of the accumulation of vorticity near the middle of the cylinder.

Five papers are devoted to two-phase gas–liquid systems. The paper of Mikitz and Rozenoff (USA) presents an analytical investigation of the rate of growth of gas bubbles in an inhomogeneous temperature field where, for growth of the bubble, heat transfer on the interphase surface rather than inertia and surface tension is the prevailing factor controlling the process. A one-dimensional spherical model of a bubble is used. It is assumed that at the instant $t = -t_W$, the liquid, uniformly heated to T_b, is brought into direct contact with the wall, whose temperature is T_W. Motion of the liquid is ignored for all instants $t > -t_W$. At instant t = 0 a bubble forms which reduces the temperature of the heating surface to T_{sat}. Beginning with the instant $t \geq 0$, growth of the bubble now occurs in an inhomogeneous temperature field.

Under such assumptions the solution is found for the one-dimensional problem of nonsteady-state heat conduction, from which the specific density of the heat flux from the liquid phase to the vapor–liquid interface and the dependence of the radius of the bubble on time, thermophysical characteristics, thermal head, and Jakob criterion are determined. This dependence includes also a new parameter, the "waiting time" t_W, i.e., the time from the initial period to that instant when growth of the bubble begins. The inhomogeneity of the temperature field is expressed in terms of this parameter. The one-dimensional dependence obtained is corrected for nonsphericity. The corrected solution for $t_W \to \infty$ approaches its analog describing the growth of a bubble in an isothermal heated medium. The model used in the study ignores heat transfer on the edges of the bubble, i.e., the transport of heat through the interface of three phases, and therefore is inapplicable in cases when the order of magnitude of the "waiting time" t_W is less than the time of bubble growth.

On the basis of their model the authors obtained the relations for the "waiting time," separation diameter, and frequency of fluctuations of the bubble. The relation between the separation diameter and frequency for various temperature gradients, pressure and heat fluxes is compared with the experiments of other authors (Van Stralen and Stanishevskii) performed on water, n-pentane, and methanol. In conclusion a formula is derived for the maximum radius of a bubble in a boiling supercooled liquid.

The paper of Yen, Jackson, and Pitts (USA) is devoted to a theoretical and experimental investigation of the occurrence and development of film boiling from a horizontal cylindrical wire in supercooled water. The physical model on which the authors' calculations are based is as follows. At some instant the temperature of a wire submerged into the liquid suddenly increases stepwise and reaches a value sufficient for the start of boiling of the medium. A vapor interlayer forms around the wire. Its thickness increases with time from zero to some value at which the interface of the vapor and liquid phases remains cylindrical. Additional assumptions are made here:

a) the temperature on the interphase surface is equal to the saturation temperature;

b) radiant heat transfer is negligibly small.

The relation being sought for the velocity of the interphase surface is derived from the energy balance on this boundary. Its mathematical formulation relates the heat expenditures for evaporation of the liquid with the algebraic sum of two components: the heat transmitted to the interphase boundary by conduction through the vapor interlayer and convection of heat through the liquid phase. To calculate the second component, the authors solve a system of one-dimensional equations of nonsteady-state convective transport of plane axisymmetric momentum, heat energy, and continuity. In this case the properties of the Newtonian fluid were assumed constant and viscous dissipation, mass losses at the phase interphase, and volume forces were neglected. A simple profile in the form of the product of some constant A (presently undetermined) and reciprocal power of the radial coordinate is obtained for the velocity of the liquid phase. By means of his profile the analytical expression is found for the temperature field in the liquid phase and its gradient on the interphase boundary. The one-dimensional problem of nonsteady-state heat conduction is solved for the vapor interlayer under the assumption of infinitesimal smallness of the diameter of the wire, constant heat flux to its heated surface, and constancy of the physical properties of the vapor. In addition, the temperature of the phase interface is assumed to be equal to the saturation temperature, irrespective of the temperature in the volume of the liquid.

As a result of the solution an analytical expression is obtained for the heat flux on the interphase surface on the vapor side. Substitution of both formulas for $\partial T/\partial r|_{r=R}$ into the aforementioned energy balance leads to the relation sought for constant A in the formula for the displacement velocity of the interphase boundary. This relation has the form of a complex transcendental function. The analytical expression for A is obtained only for small times of the process.

Further the paper presents an original method of experiments and a description of the apparatus developed by the authors for creating brief (of the order of 100 m/sec) heat pulses of a stepped form and technique of high-speed filming of the dimensions and rate of growth of a cylindrical cavity in deaerated distilled water.

Measurements revealed that the temperature of the heated surface decreased linearly with time within the first 10 msec after delivering the pulse. This confirms that the assumption made in the calculation as to the constancy of the heat flux on the heated surface was correct, at least during the initial period of development of the cavity.

Observations showed that immediately after delivering the heat pulse nucleate boiling occurs near the heated surface, the intensity of which is determined by the degree of supercooling of the liquid phase. A comparison of the authors' calculation and measurement data for several values of the heat flux of the heated surface and temperature of the liquid phase showed their good agreement. The kinetics of the actual growth of bubbles during the first 2-3 msec is faster than that given by calculation. Thereafter the calculation gives slightly overstated (15-20% within 10 msec) values of the radius.

The paper of Beer (West Germany) on boiling heat transfer stands out in the collection by virtue of its length and its saturation with new results. The paper, which is essentially a review, presents a detailed analysis of the general physical regularities of nucleate boiling.

Attention is devoted mainly to: a) heat transfer from a heated surface to the liquid phase; b) growth of bubbles on a heated surface in the presence of a heat supply from a liquid, dynamics of separation of bubbles, and motion of bubbles in a liquid.

Motion of the upward-floating bubble and the kinematic picture in its ambient medium are analyzed on the basis of the hydrodynamic potential theory in two coordinate systems – centred in the bubble and stationary. As a result of a graphicoanalytic calculation, the trajectories of the particles in the wake behind the bubble are plotted and evaluations made of some kinematic characteristics, particularly the velocity of entrainment of the liquid by the ascending bubble.

Hahn and Griffin's theory of heat transfer during nucleate boiling of a liquid is discussed in detail. Then the paper presents the procedure of the author's own experiments and gives a description of the experimental stand and measuring and recording apparatus. In the next, richly illustrated section of this paper the author considers the problem of the effect of the motion of the interface of two immiscible liquids on heat transport to a growing bubble. The disturbances of a plane horizontal interface of two liquids during passage of a bubble through it are analyzed on the basis of optical observations. Disturbances (of the turbulent type) of this boundary and additional mixing of the liquids occur in this case. Estimates are given for the surface tension and free energy both in dimensional and dimensionless terms. The dynamics of separation of bubbles is analyzed and the relations for the forces causing separation are derived in the final, fifth section.

The paper of Burmeister and Schoenhals (USA) contains an analytical investigation of the effect of pressure fluctuations of a medium on laminar film boiling near a vertical plate immersed in an unbounded quiescent medium. Such investigations were absent in the literature heretofore. The premises of the theoretical investigation are these:

a) the temperature of the isothermal heated surface is sufficiently high to maintain a regime of film boiling and vapor interlayer separating the wall from the liquid phase during all changes of pressure;

b) the pressure in the system at the initial instant is constant and the liquid in the volume phase is heated to the saturation temperature. Then the pressure changes with time reaching values lower or higher than the steady-state pressure. Spatial homogeneity of the pressure field is retained during all temporal changes. The pressure and all its derivatives with respect to time are continuous functions of time;

c) the vapor is regarded as an ideal gas, for which the product of density and viscosity does not depend on temperature, and the Prandtl number is constant;

d) the properties of the liquid phase (including the heat of vaporization) are constant;

e) a state of thermodynamic equilibrium is preserved on the vapor–liquid interface at saturation temperature corresponding to the instantaneous pressure values;

f) the curvature of the vapor–liquid interface can be ignored when formulating the boundary conditions on the interphase boundary and in the liquid phase;

g) viscous dissipation is absent in the system.

On this basis is written the initial set of equations of plane unsteady motion, continuity, and thermal energy for the vapor and liquid under the usual (for boundary layer theory) conditions of attachment to the wall, its impermeability, and continuous change of the tangential velocity component and shear stress on passing through the interphase boundary and conservation of mass and energy on it.

The solution of a system of six equations is sought by means of methods used in the unsteady boundary-layer theory. Therefore, the investigation is restricted to those conditions which provide validity to the boundary-layer hypothesis. The calculation is based on Moore's method of small perturbations. At first self-preserving transformations of the corresponding steady-state problem are sought. The nonsteady-state is taken into account by introducing a variable whose form, which depends on the variable pressure, is subsequently determined. At the final stage of the solution the temporal and spatial variables are separated by expansion of the dependent variables in Taylor series and their subsequent substitution into the system of transformed differential equations. Hence is derived an infinite sequence of ordinary differential equations for dimensionless stream functions of the liquid and vapor phase, dimensionless temperature profiles in each of the phases, and dimensionless thickness of the vapor interlayer. The equations are solved numerically. The paper presents graphs of the relations between the coefficients of series and variables of the problem and gives a comparison of the calculating results with the experimental data and calculations of other authors, and also with the Frederking and Sparrow–Sass analyses for the steady-state case of boiling in a supercooled medium. In addition, the time-averaged heat fluxes $\bar{q}$ for harmonic pressure oscillations are calculated. It is found for the first case that the heat-transfer coefficient increases with increase of pressure. In the second case the calculation gives an increase of $\bar{q}$ with increase of frequency of the pressure fluctuation and fixed amplitude, provided the frequency is above some threshold. This threshold frequency decreases with increase of amplitude of the pressure. Steady-state conditions prevail for lower frequencies, and the dynamic effects are manifested weakly. Quantitative estimates of harmonic oscillations in water indicate a 25% increase of the intensity of heat transfer at pressures slightly less than 1 atm and frequencies of the order of 5 Hz.

The last paper in the series of investigations of the hydrodynamics and heat transfer of two-phase gas– and vapor–liquid systems is contributed by Carofano and McManus (USA). It contains theoretical and experimental investigations of the motion of water–air and water–vapor mixtures in convergent–divergent nozzles.

Two systems were studied: air with water droplets suspended in it and water vapor with water droplets. This selection permits estimating the effect of noncondensing (air) or condensing (vapor) phases. The paper gives a detailed scheme of the experimental stand, a detailed description of its individual elements, and the method of measuring the main parameters of the investigated process. The convergent–divergent nozzle is made in the form of a plane channel with transparent side walls on flat sides. The design of the drop-producing sprayers, circulation system for the air and water vapor, and apparatus for measuring the pressures and temperatures is described.

The theoretical part gives a detailed analysis of the statement of the problem, its mathematical formulation, and the assumption underlying the calculation. Stress is laid on a system containing a noncondensing gas phase of the air–water type as the most characteristic. The initial mathematical formulation is based on the following assumptions and restrictions:

a) The flow is steady, uniform, and bounded by adiabatic walls.

b) The gas is nonviscous. The latter is taken into account only in the resistance forces acting on individual droplets.

c) The heat capacity and conductivity of the components of the mixture are constant. The temperature fields in each droplet are homogeneous.

d) The continuous phase is regarded as an ideal gas.

e) The phases exchange heat with one another according to the laws of heat conduction and convection.

f) The mixture is monodisperse and quasi-homogeneous on the whole. The particles do not interact with one another and are not scattered. The number of particles passing through any cross section of the nozzle in unit time remains the same; processes of nuclear condensation are absent within the flow.

g) The heat conductivity of the liquid is greater than that of the gas.

The assumption of the absence of nuclear condensation in the flow is equivalent to the requirement of nonsupersaturation of the condensing phase. It is important to answer the question of the actual effect of nuclear condensation ignored in the calculation on other processes in the nozzle sections up to the critical section (throat), where the Mach number is equal to unity. As the authors' experiments showed, the actual coordinate of the section Z_S from which nuclear condensation begins to be manifested is located behind the nozzle throat, in its divergent part, i.e., in the region characterized by supersaturation of the gas phase. Thus assumption f) is completely validated by experiment and is suitable for calculating the critical mass flow rates in the convergent part of the nozzle.

A set of integral conditions of conservation of momentum, mass, and heat energy for the mixture and liquid phase is given in the paper. To these are added some thermodynamic relations, and also the Rabin empirical formula for hydrodynamic resistance of a droplet moving with acceleration. By simple calculations and transformation a system of three ordinary differential equations is obtained which express the changes of gas velocity and temperature, and also the pressure along the nozzle. The first of these equations at point M = 1 has a mathematical singularity. To bring the calculation of the parameters to the critical section the Glaus transformation is used with replacement of the variable parameter M (Mach number) by the complex N in the form

$$N = \frac{(M^2 - 1)^2}{2}.$$

As a result of using this method a new differential equation is obtained which is not singular at point M = 1. The system is solved numerically. The results of the experiments and calculations are compared and interpreted graphically. It was shown that:

1. The measured distributions of the pressure P in the convergent part of the nozzle agree well with the theoretical predictions. However, the calculation gives noticeably understated values of P for the divergent part of the nozzle. The authors attribute this discrepancy to the effect of nuclear condensation of supersaturated vapor phase in the region behind the critical section which was ignored by the theory.

2. The critical values of the mass velocities were determined for values $0.64 \leq x_1 \leq 1$ (x_1 is the ratio of the mass flow rates of the gas and mixture at the nozzle entrance). The deviations of the calculation from the actual, measured values is 2% on the right side of the indicated range and 7% on the left.

3. The calculated values of the fluxes of mass, momentum, and heat energy for the conditions in the experiment proved to be far lower than the corresponding equilibrium values. A satisfactory explanation of this circumstance is given.

4. The theoretical model provides an adequate description of the mechanical behavior of a rapidly diverging flow charged with droplets.

The collection contains four further papers on plasma topics. The first of them, written by Anderson (USA), gives an analytical calculation of the curvature and stability of an electric arc in a transverse flow.

Unlike most previous investigators, the author of this paper bases the calculation of the curvature of the arc and its stability in a flow transversely flowing past the arc not on equations of momentum but on the equation of energy of steady motion of a gas. The latter takes into account the interaction of the heat conduction flux, convection of enthalpy, energy of the electric field, and radiant heat transfer. The simple estimates made by Anderson lead to the conclusion that in a stable arc the gas in the center of the arc should move laterally from the center of its curvature.

By substituting into the differential equation of energy Taylor's expansion of the temperature near the center of the arc and certain simplifications, a formula is obtained for the curvature of the arc. In it the radius of curvature is expressed in terms of derivatives of the temperature field (up to the third order), derivatives of the coefficient of heat conductivity, velocity components of the flow, radiant flux, density, heat conductivity, and heat capacity. All these quantities are taken for a point of the arc where the temperature reaches the maximum. Then this complex formula is simplified for the case $PePr \gg 1$ and discussed in detail. In conclusion the paper considers the problem of arc stability. It is stated that an arc is stable only when the displacement of the center of its heating as a consequence of convection is balanced by an oppositely directed displacement due to bending of the lines of force of the electric field. A decreasing of the curvature of the arc (rectification) with increase of the current strength and curving of the arc due to an increase of velocity are controlled mainly by the intensity of radiant scattering of the heat arc. Upon disturbance of the stability condition each local segment of the arc in the case of its small curvature moves in the direction of the external flow near a given segment or in the opposite direction in the case of large curvature of the arc.

The paper of Wutzke and Pfender (USA) is devoted to an experimental investigation of the electrical discharge and heat transfer of an anode in a dc arc following the application of axial friction. The voltage of the discharge and the distribution of the potentials of the electric field along the cathode in the presence of a dc arc and supersonic gas flow were measured. Attention is devoted mainly to the conditions for which it is possible to create stable arc regimes with greatly reduced heat fluxes to the anode. Experiments were carried out in a tubular arc element with an anode consisting of two separate segments. The device was equipped with a quartz window for observing the arc and its recording by means of high-speed filming. The experiments were conducted with argon and helium at pressures between 50 and 760 mm Hg and velocities at the entrance of the tubular element of the order of 160 mm/sec. The gap between the anode and cathode was varied within 2.5-5 mm, the currents were varied from 50 to 200 A. The axial arrangement of the discharge observed in the experiments is explained on the basis of the results of local measurements.

The short paper of Yen (USA) gives the derivation of formulas for calculating the thermophysical characteristics of quite nonequilibrium and highly ionized plasma. The calculation is based on nonlinear, nonequilibrium thermodynamics and Boltzmann kinetic momentum equations. One is supposed to use in this equation as independent variables the actual velocities of the particles (ions, electrons, neutral particles) rather than the relative velocities and center-of-mass velocities or their variations, as is done in the theories of Chapman, Enskog, Cowling, Grad, and Burgers. In this case the calculation of the dynamics of particle collisions is greatly simplified for non-Maxwellian velocity distribution functions. Another new element of the calculation is the use of the assumption of smallness of the ratios of the mass of electron – ion and electron–neutral particle pairs. And, finally, three-dimensional collisions are considered. The author discusses in detail the problem of the physical characteristics of such plasma to which is inherent intense currents associated with large linear diffusion velocities of electrons with increased temperature.

The authors obtained a simple formula for the coefficient of heat conductivity of ions λ_i, whence it follows that the conductivity is controlled considerably by quite mobile electrons and not by heavier ions, since

$$(\lambda_e/\lambda_i) \cong (m_i/m_e)^{1/2}.$$

(λ_e, λ_i, m_e, m_i are the coefficients of heat conductivity and masses of electrons and ions). The values of two thermodiffusion coefficients were also calculated and the graphs of their dependence on the modulus of linear diffusion velocity W were plotted. The numerical calculations, illustrated by graphs, for a monatomic gas show the presence of a sharp peak on these curves with approach to the sound velocity threshold of the electrons.

The concluding paper from this series belongs to Pentri and Pfender (USA) and is devoted to measurements of local heat transfer in plasma by means of a floating wire sensor. A new method is proposed for determining the local values of the heat-transfer coefficient of a wire immersed into an axisymmetric high-temperature, high-density plasma arc. The idea of the method consists in the uniform displacement of a fine tungsten wire with a current across the plasma filament. Then with a change of the distance x from the periphery to the axis of the plasma filament its electrical resistance will change. Consequently, with constancy of the current supplying the wire the voltage drop V on the section of the wire bathed by the plasma will be variable. The quantity V(x) is transformed numerically to local values of the temperature and heat flux. The local values of the intensity of heat transfer of a nonadiabatic surface bathed by a high-velocity flow of highly ionized plasma were measured on the basis of this method. The experiments were carried out in a cylindrical stainless steel chamber with water-cooled walls (diameter 45 cm, height 30 cm) with an anode coated with a deoxidized copper film and cathode of thoriated tungsten. The air was preliminarily pumped from the chamber to 10^{-6} mm Hg. Then the chamber was filled with argon to atmospheric pressure, after which an arc discharge was created. The wire, from 0.25 to 0.375 mm in diameter, fastened in a special holder, was moved uniformly normal to the plasma filament at speeds of 25.4 and 11.43 cm /sec in various sections over the height of the plasma filament. The paper discusses the details of the measuring and recording apparatus, and also methods of machine conversion of the electrical quantities to thermal. The measurement results for an argon arc (temperature fields in the plasma, distribution of the heat-transfer coefficients along the wire) are analyzed.

The paper of Ibele and Desmond (USA) contains a calculation of some transport characteristics of air–methane gas mixtures. The authors were motivated to undertake this problem by the requirements of astronautics in connection with future flights of satellites to Jupiter whose atmosphere consists of hydrogen and methane.

The paper presents in the form of graphs and tables the numerical data for dimensionless coefficients of viscosity, heat conductivity, heat capacity, and Prandtl number as a function of the concentration (mole fractions) of hydrogen in the mixture at fixed temperatures (every 100°K from 200 to 1500°K). The calculations were performed by the method presented in Hirschfelder, Curtiss, and Bird's book. With an increase of the concentration of H_2 the viscosity decreases continuously, and the more intensely, the higher the temperature. Heat conductivity under these same conditions, conversely, increases monotonically. The Prandtl number as a function of the composition changes nonmonotonically and passes through a minimum, which descends lower and shifts to the right, to the side of increasing H_2 concentrations, with an increase of the absolute temperature of the mixture.

Of considerable interest for engineering applications is the theoretical and experimental investigation of Eisel, Leidenfrost, and Mantanajagals (USA) devoted to bladed rotary heat exchangers of the propeller type. The device represents a propeller with two, four, and more hollow laminated blades rotating without an angle of attack. A coolant circulates inside the blades. Such heat exchangers owing to intense external convection effectively transmit heat to the ambient gas. It is possible to achieve in it large values of the heat-transfer coefficient from the gas side, of the order of 500 W/m^2.

The investigation was stimulated by the fact that, according to Wasserman's observations, the relation $\overline{Nu} = f(\overline{Re})$ for a rotating blade is much steeper than for longitudinal flow past a plate. In the authors' opinion, such intensification may be due to the effect of the radial and axial components of acceleration and corresponding secondary motions due to centrifugal and Coriolis forces.

The analytical part of the paper is based on the following assumptions:

a) the blade is infinitesimally thin, semibounded, and rotates in a quiescent incompressible isotropic gas medium, with constant physical properties; gravitational effects are small.

b) Motion is steady-state and without dissipation.

The calculation is carried out for laminar and turbulent flow regimes and is based on the Karman–Pohlhausen method of a layer of finite thickness. Integral conditions relative to the azimuthal and radial components of friction and thickness of the boundary layer (losses of momentum and displacement) are derived for reversed motion. These equations are then simplified on the basis of comparative estimates and elimination of some terms. The assigned parabolic profiles of the azimuthal and radial velocity components in the section of the layer differ in no way from those which are usually taken in analogous calculations of a two- and three-dimensional boundary layer of a stationary plate in an oblique flow (with an angle of attack). As a result expressions are obtained for local and total (averaged over the chord of the blade) drag coefficients $\overline{C}_f$ in the form of a two-member product. The first multiplier represents the drag law for a stationary plate in longitudinal flow and the second plays the role of a correction coefficient taking into account the specific character of the rotational motion and effect of mass, centrifugal, and Coriolis forces. This correction multiplier, and along with it the values of $\overline{C}_f$ for sections of the blade close to the axis of rotation, is higher than for the end sections. Thus, for short and broad blades the three-dimensional effects can reach large values. For example, for aspect ratios of order two the difference between $\overline{C}_{f\,\text{two-d}}$ and $\overline{C}_{f\,\text{three-d}}$ reaches 100%. The expressions for the local and average Nusselt numbers are obtained by means of the known Reynolds analogy between friction and heat transfer.

The turbulent boundary layer is calculated likewise. It is based on the aforementioned integral conditions of the average motion, on the "one-seventh" profile, and on the Blasius law of turbulent resistance. However, the expressions obtained in this case for C_f and Nu differ from their laminar analogs in that the radial velocity component makes an extremely small contribution.

The setup of the experiment, its procedure, apparatus, and the results and their analysis are discussed.

The relations between the Nusselt numbers and the Reynolds number are plotted from the measurement data for various y/b (b is the chord length). The experiments confirm an increase of Nusselt numbers with increase of y/b and fixed Reynolds number. This effect degenerates for quite large y/b. Thus, in the case of long rotating blades the heat-transfer coefficient can be calculated from known formulas of the two-dimensional boundary layer theory. Another important conclusion consists in that the critical Reynolds numbers characterizing transition to a turbulent flow regime are lower for a rotating plate than for a fixed one, and amount to about 10^4.

The collection will undoubtedly be a great aid for engineers, students, teachers, and researchers interested in convective transport processes.