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HEAT TRANSFER—A REVIEW OF 1970 LITERATURE

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INTRODUCTION

THIS review surveys research in the field of heat transfer, the results of which have been published during 1970 or late in 1969. The number of papers in this field is such that only a selection can be included in this review. A more detailed listing is contained in the *Heat Transfer Bibliographies* published periodically in this journal.

The outstanding conference in the field of heat transfer during the period covered by this review was the Fourth International Heat Transfer Conference held at Versailles, France from August 31 through September 4, 1970. Approximately 1000 attendants listened to presentations by reporters in thirty-six sessions, participated in the discussions of the papers, in panel meetings, and in round table discussions. Thirty-six sessions were devoted to the fields: conduction, forced and natural convection, condensation and boiling, radiation, combined heat transfer, heat exchangers, rheology, and measurements techniques. The Max Jakob medal was presented to Academician S. S. Kutateladze at the opening session. This ceremony was followed by a film presentation on visualization of heat transfer to which U. Grigull gave oral explanations. One of the panel sessions was devoted to the subject: "Heat Transfer Research in the Seventies," based on a written report by R. H. Sabersky. The papers presented at the conference, together with the discussions, are available in book form at Elsevier Publishing Company, Amsterdam, The Netherlands. The conference was followed by the Third International Seminar on Heat and Mass Transfer which was devoted to the field of rheology and organized by the International Centre for Heat and Mass Transfer at Herzeg-Novi, Yugoslavia. The proceedings will be published in the series "Progress in Heat and Mass Transfer" by Pergamon Press.

A number of conferences devoted special sessions to the field of heat transfer. The Joint Fluids Engineering, Heat Transfer, and Lubrication Conference was held in February of 1970. The heat transfer sessions dealt with change of phase, internal convective flows, two-phase flows, boiling, and heat transfer in cryo-deposits. The Fifteenth Annual International Gas Turbine Conference in Brussels, Belgium organized three heat transfer sessions dealing with boundary layers, rotating flows, transpiration cooling, and heat exchangers. The Space Technology and Heat Transfer Conference at Los Angeles in June, 1970 had sessions on aerodynamic heating, spacecraft heat transfer, heat transfer in propulsion systems, plasma and cryogenic heat transfer and heat pipes. Preprints for the papers presented in these three meetings are available through the American Society of Mechanical Engineers. The 1970 Heat Transfer and Fluid Mechanics Institute, held in June, 1970 at Monterey, California, presented five invited lectures, of which the lecture by H. Schlichting covered the topic, "A Survey of Some Recent Research on Boundary Layers and Heat Transfer," and a lecture by F. Kreith was on "Heat and Mass Transfer in Ecological Systems." In addition, approximately half of the papers of the conference were devoted to heat transfer. The Proceedings are available at the Stanford University Press.

The Ninety-First Winter Annual Meeting of the American Society of Mechanical Engineers, held at New York, New York in November, 1970, included four sessions on various topics of heat transfer, panel discussions on cryobiology and on vibration in heat exchangers, symposia on liquid metal heat transfer, on semi-transparent materials, on environmental effects, and on augmentation of convective heat and mass transfer. An open forum gave participants the opportunity to report informally on recent research results. Preprints of these papers are available. At the same time, the Annual Meeting of the American Institute of Chemical Engineers was conducted at Chicago, Illinois. Two symposia dealt with heat transfer with change of phase. The papers presented there will be contained in a special issue of the Chemical Engineering Progress Symposia Series.

A list of books in the field of heat transfer or in related fields can be found at the end of this review. A considerable number of films on heat transfer processes have been collected. Copies are available through the Engineering Societies Library, 345 East 47th Street, New York, New York.

Developments in research on heat transfer problems during 1970 can be highlighted by the following remarks: The effects of contact resistance, variable properties, freezing, and melting were considered in heat conduction processes. Several papers present charts describing the time-varying temperature field for various geometries and boundary conditions. The heat balance integral was applied to various conduction problems. Papers on channel flow dealt with variable properties, swirling and unsteady flow, non-Newtonian fluids, non-circular ducts, and the influence of axial heat conduction. The interaction between heat conduction in the duct walls and heat transfer in the fluid, as well as unsymmetric boundary conditions was studied. Boundary layer analyses considered unsteady situations in laminar and turbulent flow. Measurements for turbulent boundary layers were reported. Impingement of jets and jet mixing were investigated and experimental results on turbulent transfer parameters were reported.

In natural convection, attention was focused on enclosures, on mixed free and forced convection, on finite horizontal surfaces, on transient conditions, and on detailed investigations of turbulence and stability. Liquid film cooling, gaseous film cooling with three dimensional injection, and the use of various gases as coolant found special attention. Computer data banks are available for the determination of the various flow regimes in two-phase flow. In-line flow of liquid metals through rod bundles was investigated. Extrapolation techniques, variational methods and Monte Carlo schemes were proposed for the solution of the equations describing low density heat transfer. Various models to calculate radiative heat transfer in participating non-gray media were employed with scattering included. Problems with simultaneous conduction or convection and radiation were solved.

A new section in this review deals with plasma heat transfer and reports on the effects of deviations from local thermodynamic equilibrium, on the effect of convection in electric arcs, and on electrode heat transfer. Thermal protection systems for space vehicles and astronauts, heat pipes, and heat exchangers found special attention in the area of heat transfer applications.

To facilitate the use of this review, a listing of the subject headings is made below in the order in which they appear in the text. The letter which appears adjacent to each subject heading is also attached to the references that are cited in that category.

Conduction, A
Channel flow, B
Boundary-layer flow, C
Flow with separated regions, D
Transfer mechanisms, E
Natural convection, F
Convection from rotating surfaces, G
Combined heat and mass transfer, H

Change of phase, J
Radiation, K
Liquid metals, L
Low-density heat transfer, M
Measurement techniques, P
Heat exchangers, Q
Aircraft and space vehicles, R
General applications, S
Plasma heat transfer, T
Thermodynamic and transport properties, U

CONDUCTION

Various topics in steady-state conduction were studied in recently published papers. The critical radius of insulation in cylindrical and spherical systems is decreased when account is taken of the radius dependence of the convective heat transfer coefficient h; a reduction in the critical radius also occurs when the dependence of h on the temperature difference in natural convection is taken into account [62A]. The presence of a local heat sink on the surface of a solid, for example, a fin or a thermocouple, brings about a depression of the temperature at and adjacent to the sink; in the case of a thermocouple, an error in temperature measurement results, whereas for a fin, the heat transfer rate is reduced below that predicted by conventional methods which neglect the temperature depression [28A, 63A]. Inequalities governing the exponential decay of the temperature field as a function of distance from a surface source were deduced by elegant mathematical arguments [20A].

Numerical solutions of Laplace's equation yielded shape factors for steady conduction across a plane or curved strip containing regularly spaced circular holes [57A]. Graphical results are given for the heat flux passing through a solid slab maintained at a constant temperature on one surface and heated (or cooled) by equally spaced isothermal strips on the other surface [59A]. Singular perturbation techniques were employed to analyze the temperature field in a hot wire anemometer positioned normal to a wall and exposed to a parabolic velocity profile; such a device has potential application for measuring velocity gradients at the wall in turbulent shear flows [2A]. The solution of Laplace's equation for the region external to a semi-infinite rod was reduced to a Fredholm integral equation of the second kind [41A]. Successive over-relaxation, together with a method for coping with boundaries that do not fall on grid points, was used in the finite-difference solution of Laplace's equation in spherical coordinates with axial symmetry [32A]. The tendency of transient solutions to exponentially approach steady state served as the basis of an efficient extrapolation method for determining steady-state results via finite differences [60A].

Techniques for dealing with variable thermophysical properties have been developed. Steady state solutions for arbitrarily shaped solids with temperature-dependent thermal conductivity and convective or temperature boundary conditions can be obtained in algebraic form by employing a least-squares technique which involves iterative computations only at a discrete set of boundary points [64A]. A series expansion of the temperature in terms of a small parameter has been proposed as a method for solving steady and unsteady heat conduction problems with temperature-dependent conductivity and specific heat [69A]. The method of Meksyn, originally devised in connection with the boundary layer equations of fluid mechanics, was used to solve the transient heat conduction problem in a semi-infinite solid with temperature-dependent conductivity and constant surface heat flux [16A]. The existence and significance of similarity solutions for the semi-infinite solid with temperature-dependent conductivity were established by mathematically rigorous arguments [52A]. Calculations showed that the accounting of variable properties may significantly influence the heat transfer rates deduced from the measurement of transient surface temperatures for a one-dimensional solid [14A]. A nonlinear estimation method involving finite differences was formulated and applied for solving the inverse problem of transient heat conduction for solids with temperature-dependent thermal properties [5A].

Heat generation effects were also investigated. For solids with internal heat generation which depends nonlinearly on temperature, both numerical solutions and analytical bounding techniques were employed to establish the relationship between the hot spot temperature and the intensity of heating [37A]. The steady temperature field in an externally insulated electric conductor with linearly temperature-dependent thermal conductivity and electrical resistivity was solved in the limiting cases of low and high Joule heating [13A]. Experiments on the coupled thermal and electrical phenomena at the P–N junction of a semi-conductor provided information about the temperature rise due to the Peltier effect [38A].

Thermal contact resistance continues to be an active topic. Plating of a base material of low thermal conductivity with a material of high thermal conductivity can cause a substantial reduction in the thermal contact resistance [48A]. For orthotropic anisotropic materials, the contact resistance depends on the orientation of the contact interface and the ratio of the directional conductivities, as well as on the parameters which govern isotropic contacts [67A]. Measurements of thermal contact resistance at gold foil interfaces showed a pressure dependence suggesting that both elastic and plastic deformation of the surface structure occur in a manner determined by the sequence of the pressure changes [50A]. The thermal constriction resistance was explicitly related to nonuniform surface conditions and applied to the calculation of the macroscopic contact resistance caused by nonuniform contact points distribution [47A]. Measurements of the minimum thermal resistance at soldered joints between brass and brass, brass and stainless steel, and stainless steel and stainless steel were correlated by a parameter from thermal constriction theory [71A]. Correlation of contact resistances measured for stainless steel and molybdenum specimens at pressures of 10^{-4} mmHg was achieved by a grouping involving the mean height of the microprojections [45A].

The directional effect, whereby the contact resistance is different depending on the direction of heat flow, has been observed for contact between similar materials [65A]. Electrolytic analogue experiments were undertaken to explore the influence of the distribution of contacts on the thermal contact resistance [15A]. A proposed insulation arrangement for an 1100°C liquid metal MHD system makes use of the contact resistance between ceramic and metal members; measurements at a nickel–alumina interface showed a pressure dependence in agreement with theory, but the contact conductance was below the analytical prediction [27A]. Although not concerned specifically with thermal contact resistance, the findings of an in-depth analytical and experimental study of the mechanism of contact between solid surfaces should be useful to investigators of the thermal contact problem [29A–31A].

Heat conduction problems involving phase change were analyzed in a number of papers. When a solid cylinder is immersed in a liquid such that the initial temperature of the solid is below the freezing temperature of the liquid, an annular solidification layer grows on the surface of the cylinder and then subsequently decays [35A]. A growing boundary layer of frozen materials builds up on the surface of a flat plate whose surface temperature is dropped and then maintained below the freezing temperature of a liquid flowing past the plate [49A]. Short-time solutions for melting of a slab due to a surface hot spot showed that the melting progresses much faster along the surface than into the material [68A]. For the melting of a cylinder under arbitrary heat inputs applied at its outer bounding surface, an analytical short-time solution was supplemented by numerical solutions covering all time [43A]. A finite-difference scheme for multi-dimensional solidification problems was applied to several problems involving metallic castings [42A].

The freezing or melting of a spherical region was solved approximately to obtain a correction factor for the spherical geometry, the accuracy of which was checked by a finite-difference solution [11A]. A one-dimensional model for a material that undergoes charring and surface ablation or surface erosion-ablation was formulated for the quasi-steady state characterized by a temperature field which changes only slightly with time in a coordinate system measured from the moving surface [56A]. Conformal mapping was used to find the shape of a boundary at which the temperature and heat flux are specified, and application was made to a frost region which is situated on a cooled surface and is heated by thermal radiation [24A]. Conditions for uniqueness of solution were derived for a slab which melts under an applied heat input which depends both on time and on the melted depth [7A]. The results of an experiment concerned with the freezing of water in a corner were affected by free convection currents generated by the density inversion at 39°F [36A].

Analyses of various transient problems have been carried out. Graphical presentations of temperature–time results are now available for: the slab, cylinder, and sphere with suddenly applied uniform internal heat generation and convective heat loss [70A]; the slab which exchanges heat on its two surfaces with fluids of different temperatures and convective heat transfer coefficients [23A]; the cylindrical shell with a suddenly applied step in surface heat flux [53A]; and the slab, cylinder, and sphere subjected to convective exchange with a fluid whose temperature increases linearly with time [54A]. When transient heat conduction is confined to a thin layer near the surface of a solid, the temperature solution is usually approximated by that for a semi-infinite solid; a generalization of this approach has been developed for curved surfaces [44A]. A method was devised for solving the unsteady heat equation in the case in which the bounding surface of a solid changes with time while maintaining a similar shape [25A]. A series solution method in the Laplace transform plane developed in connection with a convection problem for a fluid sphere, might also prove useful in transient heat conduction problems [9A].

The transient temperature field in a semi-infinite solid subjected to an instantaneous surface source at time = 0 and to convective boundary conditions was solved as an adjunct to a thermal stress problem [40A]. Limiting solutions were used to construct a complete solution for the time-varying heat flux at the surface of an isothermal cylinder surrounded by a thick layer of insulation [12A]. Convective heat transfer coefficients can be deduced from temperature measurements used in conjunction with a solution of the heat conduction equation for a wall separating two fluids, one of which has a sinusoidally varying temperature [34A].

Refinements and applications have been made of the Heat Balance Integral. The typical formulation of the Heat Balance Integral involves the spatial integration of the unsteady energy equation. Better results are purported to be obtainable when an integral equation is deduced by performing two integrations of the energy equation [66A]. Such a doubly-integrated Heat Balance Integral was used to solve for the coating thickness in the fluidized-bed coating process, whereby a preheated object is placed in a fluidized bed of a polymer powder [22A]. To cope with initial nonuniform temperature distributions, a generalization of the Heat Balance Integral was proposed in which integral equations are generated by taking moments and then integrating the energy equation [6A]. The Heat Balance Integral, supplemented by the approximation of one of the participating integrals, yields an equation for the thickness of a frozen layer on a cooled wall when the adjacent liquid is in convective motion; the method circumvents the need to assume an expression for the temperature profile [21A]. The initial transient in a slab subject to surface convection and radiation was solved by applying the Heat Balance Integral [58A].

Solutions were obtained for conduction problems with radiation boundary conditions. Increasing the thermal conductivity of an aerodynamically heated, radiating heat shield was shown to be effective in decreasing temperature variations within the shield material [46A]. The presence of a narrow gap in a thin, rotating, solar-heated cylindrical shell caused perturbations of the circumferential temperature distribution which were confined primarily to the region of the gap [19A]. Finite-difference solutions provided results for a graphical presentation of temperature histories for a sphere losing heat by radiation to a zero temperature environment [3A]. Analyses of radiating fins included: annular fins of trapezoidal profile, but without consideration of base surface interaction or incident radiation from other sources [39A]; two-dimensional numerical solutions for cylindrical fins with surface convection and radiation, with account being taken of radiative interaction between fin and base [61A]; black or gray cylindrical fins, with or without base surface interaction [17A]; radiation-heated fins related to applications involving steam generator tubes [55A].

Heat conduction solutions motivated by machining, cutting, welding, laser heating, and similar applications were performed. These included: a rotating disk, heated on a portion of its rim and cooled by convection from its lateral faces [26A, 51A]; a moving semi-infinite solid or a rotating cylinder, respectively with a band heat source on the exposed or lateral surface, cooled by convection [18A]; a thin plate subjected to surface heat sources and convection cooling [8A]; two semi-infinite solids which model sliding contact [4A]; a pair of surfaces which meet and separate according to a regular cyclic pattern [33A].

The finite speed of propagation of the temperature wave in a semi-infinite solid depends on the instantaneous values of the thermal conductivity and specific heat of the solid [1A]. The properties of temperature rate waves of arbitrary form were examined by means of a highly mathematical analysis [10A].

CHANNEL FLOW

Techniques for augmenting the heat transfer performance of duct flows continue to attract the interest of investigators. Experiments indicated that local fluid injection into a turbulent pipe flow increases the heat transfer coefficient downstream of the injection station; both the injected and the mainflow fluids were water [69B]. The heat transfer efficiency (based on the same pumping power) of a duct consisting of a sequence of diverging and converging sections was found, on the basis of turbulent airflow tests, to be better than that of a duct of constant cross section [38B]. Heat transfer and pressure drop experiments for gas flow in spirally corrugated tubes showed them to be highly effective heat exchangers; for example, in one case, for equal pumping power, a corrugated tube had a heat transfer coefficient 22 per cent greater than that for a smooth tube [37B]. Experiments were performed with swirling airflow in a tube, the swirl being induced either by stationary vanes or by tangential injection; for turbulent flow and Reynolds numbers below 10^5, the swirl flow was found to transfer heat more efficiently than a non-swirling flow [70B]. A model based on a rigid-body rotation impressed on an axial flow was employed to qualitatively explain the effect of rifling on heat transfer and friction in a turbulent pipe flow [75B]. Calculations of the decay of an initial swirl in a turbulent pipe flow showed that the effects of swirl on the heat transfer and friction persist to about 20 pipe diameters [49B].

Augmentations in heat transfer by an order of magnitude were achieved by subjecting a water flow through a tube to a rotary space vibration [56B]. Turbulence intensity measurements in the region downstream of an orifice in a tube were employed to explain the high local heat transfer coefficients and to correlate the available results downstream of the separated region [25B]. Experiments on the effect of pressure fluctuations on turbulent heat transfer to air in an electrically heated tube showed that the influence of the fluctuations decreases when the fluctuation frequency departs from the resonant frequency [28B]. For the conditions of unsteady heating and constant flow rate and of steady heating and time-varying flow rate, experiments involving turbulent gas flow in tubes gave instantaneous Nusselt numbers which differed appreciably from the corresponding quasi-steady Nusselt numbers [39B].

Additives also affect the heat transfer characteristics. Experiments on turbulent pipe flow of a gaseous suspension showed that the presence of the solid particles may either decrease or increase the heat transfer, depending on the pipe diameter and the Reynolds number [10B]. In an experiment performed with suspensions of glass beads in a turbulent air stream flowing in a horizontal electrically heated tube, the Nusselt numbers were as much as $2\frac{1}{2}$ times larger on the bottom of the tube than on the top, owing to stratification [22B]. Small percentages of high molecular weight additives to a water solvent reduced the turbulent heat transfer to as low as 20 per cent of that for pure water and brought about a dependence on the tube diameter; the effect was explained by a thickening and stabilization of the laminar sublayer [19B].

Several investigations concerned with the influence of variable fluid properties have been carried out. The results of turbulent airflow experiments in an annulus could be correlated by multiplying the Nusselt number with the factor $(T_w/T_b)^{0 \cdot 2}$, both for the entrance and for the developed regions [48B]. Values of the T_w/T_b ratio as low as 0·12 were encountered when arc-heated, turbulent air was passed through a water-cooled tube, and a Nusselt–Reynolds–Prandtl correlation was achieved by using bulk fluid properties [57B]. Heat transfer data are also reported for partially ionized argon flow in a water-cooled circular tube, the entering gas temperature being 21 000°R; measured Nusselt numbers based on the enthalpy difference and on bulk properties agreed well with laminar, constant property results after the first 5–10 diameters [59B]. Turbulent heat transfer studies involving superheated steam were performed to determine the influence of variable properties, temperature field development in the entrance region, and duct configuration (i.e. tube or annulus) [40B]. An examination of available correction factors accounting for variable property effects in correlations of turbulent heat transfer information has been carried out, and a new correction factor, purported to be valid for liquid or gases and for heating or cooling is proposed [31B].

Improved analytical predictions for the Nusselt number in strongly heated turbulent gas flows (i.e. with large property variations) in the quasi-developed region of a tube were obtained by finite-differences in conjunction with a modified van Driest mixing length model [45B]. The authors of [45B] have also developed a flexible computer program applicable to strongly heated gas flows in the entrance region, both for turbulent and laminar conditions [5B]. Examination of the governing equations for laminar duct flows revealed that there is a dimensionless modulus associated with the viscosity-temperature variation [72B]. A step-by-step computation, taking account of variable properties for transformer oil, was performed to determine local laminar Nusselt numbers in the entrance and developed regions of a vertical parallel-plate channel [1B]. The Kirchhoff transformation, well known in heat conduction theory, was used to facilitate the solution of Couette flow with viscous dissipation and with temperature-dependent viscosity and thermal conductivity [50B].

Large property variations also occur in fluids near the critical state. New experiments involving carbon dioxide, taken together with other available results, indicate various operating regimes which depend on the mass velocity, a heat flux parameter, and the relative importance of forced and free convection; depending on the regime, varying degrees of improved or deteriorated heat transfer are possible [63B]. Another investigation of supercritical carbon dioxide in turbulent pipe flow systematically studied the dependence of the wall temperature distribution on the inlet fluid temperature, the pressure, the wall heat flux, the mass flow, and the direction of flow (upward or downward) [11B].

High rates of heating may bring about a transition from turbulent flow to laminar flow. Experiments involving gas flows in tubes have demonstrated such a transition phenomenon [4B, 18B]. The relaminarization can be characterized by an acceleration parameter similar to that used for external flows [44B]. In some cases, laminar values for the heat transfer coefficient were found to prevail at Reynolds numbers above that for laminar-turbulent transition [4B, 18B].

Non-Newtonian fluids are encountered in a variety of technologies. The solution of the Graetz problem for mass transfer for non-Newtonian flow in a tube with permeable walls was motivated by a blood flow application; specifically, in connection with the design of haemodialyzers used in the medical field to treat patients who are acutely uremic [20B]. Applications to liquid food products prompted the study of non-Newtonian liquid flow and heat transfer in the entrance region of a tube; viscosity variations were accounted for, and the analysis consisted of an integral formulation near the inlet and a finite-difference solution farther downstream [46B]. Solutions of the Graetz problem for power-law non-Newtonian flow in annuli gave rise to higher Nusselt numbers than for Newtonian flow when the power-law exponent is between zero and one [32B]. Analytical results for the dispersion of solute in turbulent flow of a power-law fluid indicated that the intensity of the dispersion increases with the exponent of the power law at fixed values of the Reynolds and Schmidt numbers [74B]. Measurements of heat transfer, pressure drop, and velocity and temperature profiles in dilute aqueous solutions of high polymers showed the Deborah number to be an additional parameter besides those for a Newtonian flow [35B]. Heat transfer data for non-Newtonian flow in coiled pipes were found to depend on the power-law exponent as well as on the ratio of the tube and coil diameters [54B]. Radial temperature measurements in tube flow of an extruded polymer revealed a maximum situated a short distance away from the wall [17B].

Various aspects of turbulent heat transfer were investigated experimentally. Heat transfer measurements in an annular duct with axially varying cross-sectional area showed that fully developed Nusselt numbers for annuli with uniform cross section cannot be applied locally for accelerating flows in annuli [27B]. Spectral measurements of temperature and velocity fluctuations in a fully developed pipe flow indicated that a strong relationship exists between the temperature and velocity fields at low wavelengths, but not at high wavelengths [13B]. Experiments with water and with water-glycol mixtures in longitudinal flow through a heated rod bundle provided a Nusselt–Reynolds–Prandtl correlation in which the pitch-to-diameter ratio appears as an additional parameter [55B]. Heat transfer results for airflow in a square duct were correlated by the same equation used to correlate triangular duct results [6B]. Experiments were carried out in a rectangular duct with asymmetric heating [67B].

Analytical studies of several turbulent heat transfer problems have been reported. Account was taken of the Reynolds number and radius ratio dependences of the non-dimensional velocity profile in a Graetz-type analysis for annuli with boundary conditions of either prescribed wall heat flux [52B] or prescribed temperature [53B]. The Nusselt numbers for the former case generally exceeded those for the latter. The Sturm-Liouville problem that arises in the analysis of the Graetz problem for uniform wall heat flux was attacked by the method of matched asymptotic expansions [65B]. A modified form of the van Driest damping factor was employed in the analysis of the effect of wall suction on friction, heat transfer, and mass transfer in pipe flow; suction substantially increased both the friction factor and the Nusselt number [36B]. For calculations of turbulent mass transfer in a binary gas mixture with suction at the tube wall, the coefficients in the logarithmic velocity profile were represented as linear functions of the suction velocity [43B].

The condition for the attainment of a thermally developed regime in duct flows is that $q \sim e^{mx}$ (q is the local heat flux, x is the axial coordinate), which includes uniform wall temperature and uniform heat flux as special cases. Fully developed heat transfer results for laminar and turbulent flows in tubes, channels, annuli, and tube bundles were generated for parametric values of a quantity F_0 which is related to m [30B]. A method, based on a finite-difference solution of the temperature field in a duct wall, is proposed for deducing inside wall temperatures and heat transfer rates from outside wall temperature measurements, thereby facilitating the evaluation of heat transfer coefficients [61B]. A numerical method for calculating fully developed laminar velocity profiles from given temperature profile data was successfully tested with the classical Graetz problem and with a temperature profile corresponding to a highly distorted non-Newtonian velocity profile [9B].

Laminar heat transfer in non-circular ducts attracted the interest of a number of investigators. Finite-difference solutions for developed flow and heat transfer in curved rectangular channels provided information on the effect of Dean number, aspect ratio, and Prandtl number [14B]. A variational method and a point matching technique were employed for solving for the fully developed Nusselt number and friction factor for several non-circular cross sections [15B]. Available analytical and experimental information for laminar heat transfer and friction in triangular ducts was brought together, and the experimental results were correlated in a form convenient for engineering application [60B]. A correlation of laminar heat transfer results for annular ducts successfully eliminated the radius ratio as a parameter [51B]. Finite-difference solutions for laminar flow and heat transfer (or mass transfer) in a corrugated duct indicated that results for this geometry cannot be adequately estimated from available information for tubes and channels, and that the results also differ considerably from those for a triangular duct [62B]. On the other hand, the Nusselt number results for a parallel-plate channel served as a basis of an approximate method for computing the heat transfer characteristics of narrow ducts [34B]. Flow visualization using fluorescein dye in water revealed the existence of a pattern of vortices in the entrance region flow of a concentric sphere heat exchanger [12B].

Laminar analyses also dealt with the effects of axial conduction, duct wall interaction, and unsymmetric boundary conditions. Further study of thermally developed tube flow with uniform wall temperature confirmed that axial conduction could be neglected for Péclét numbers greater than 10 [3B]. The effect of axial conduction in the Graetz problem for an annulus was analyzed by constructing separate solutions for the upstream and downstream regions (unheated and heated, respectively) and then matching these solutions at the cross section where heating begins [33B]. An analysis of laminar hear transfer in a channel with a uniform heat flux boundary condition showed that axial conduction in the channel wall decreases the Nusselt number relative to the case in which the wall effect is neglected [21B]. A combined numerical and analogue method was employed to solve the unsteady thermal entrance region in the presence of a thermally participating tube wall, axial conduction, and a steady, developing velocity field [41B]. A mathematical formulation, including axial conduction, was outlined for dealing with unsteady laminar heat transfer in a tube with steady, developed velocity and time-dependent thermal boundary conditions, but the actual solution was not carried out [24B]. An analysis for circumferentially varying heat flux in the thermal entrance region of a laminar tube flow showed that for the same amplitude, the first harmonic has a greater effect on the wall temperature or the Nusselt number than do higher harmonics [7B]. The solution for laminar heat transfer in a tube subjected to incident thermal radiation on a portion of its circumference and to radiative losses to the environment required that a finite-difference method be employed [64B].

Other thermal entrance region studies have been published besides those discussed in earlier paragraphs. A variational formulation in the Laplace-transform domain, used in conjunction with the Ritz–Galerkin technique, was outlined for solving unsteady laminar heat transfer problems of the Graetz type, but the example problems were restricted to the steady state [58B]. The slug flow Graetz problem for convective boundary conditions at the wall of a circular tube was solved exactly by Laplace transform and approximately by a variational method, with a specific example being worked out to test the accuracy of the latter [29B]. A solution method, based on integral forms of the mass, momentum, and energy equations, was described for laminar, compressible gas flow in the entrance region of a duct, but the solution was not worked out and no results were given [73B].

Problems of phase change coupled with laminar duct flows have been investigated. Basic results for heat and mass transfer in a channel with mass addition or withdrawal at the bounding walls were employed to solve for evaporation or sublimation from a film on one of the walls [66B]. Experimental data on laminar tube flow of liquid water with a layer of ice on the inside surface of the tube indicated an important effect of natural convection [23B]. Variational methods were used to solve the coupled energy equations for laminar flow in a tube whose inner surface is coated with a growing solidification layer [8B].

Laminar mass transfer problems for duct flows are generally closely related to heat transfer problems. The effect of axial diffusion on steady-state mass transfer of decaying products resulting from the disintegration of an inert gas in a laminar tube flow gives rise to a Péclét number effect analogous to that encountered when axial conduction is accounted in the Graetz problem [68B]. Laplace transformation followed by a perturbation technique with a strained coordinate was employed to solve for the time-dependent concentration distribution in laminar tube flow at low Péclét numbers [16B]. The coupled heat and mass transfer in a tubular reactor, including a non-first-order chemical reaction, was solved for laminar and slug flow by finite differences [47B]. Available models for the non-isothermal, homogeneous, first-order, irreversible, laminar gas flow tubular reactor were compared and extended [2B]. Diagnosis of errors in a dye displacement technique of velocity measurement motivated analytical solutions for unsteady laminar diffusion and convection for liquid flow in a tube [76B].

For fully developed, laminar, magnetohydrodynamic flow in rectangular ducts of finite aspect ratio, the accounting of variable properties led to significant differences in friction factors and flow rates relative to those for the constant property case [71B]. An integral form of the mechanical energy equation was used in conjunction with the usual integral momentum and energy equations to solve for the simultaneously developing velocity and temperature fields in laminar, magnetohydrodynamic channel flow [42B].

Large amplitude acoustical oscillations (Sondhauss oscillations) can be generated by heat addition to gas in a tube having one end open and the other end closed [26B].

BOUNDARY-LAYER FLOW

Laminar boundary layers

A number of solutions was reported for heat transfer in steady laminar boundary layers. The recovery factor obtained from similar solutions [25C] for a hypersonic boundary layer of gas ($Pr = 0.723$, $c_p = \text{const}$, $\mu \sim T$) varies from 0·814 to 0·871 for $\beta = 1$ to -0.216 (separation). The gap existing for a boundary layer description on a blunt object between the stagnation line solution and the Falkner–Skan solution for wedge flow was bridged [11C]. Heat transfer results for an axisymmetric boundary layer on a moving circular fiber [6C] extended previously published work on moving surfaces. The boundary layer equations were solved [24C] after transformation of the equations to Görtler variables by numerical integration for water flowing over a flat plate with an exponentially decreasing surface temperature and with experimentally determined values for the fluid properties. Boundary layer thickness, friction factor and Nusselt number were calculated. Streamwise heat conduction affects the heat transfer in a forced convection boundary layer of a liquid metal over a flat plate without or with superimposed free convection when the Peclet number is smaller than a value between 7 and 12 [27C]. The influence of variable transport properties on low Reynolds number flow past a heated circular cylinder was investigated [15C]. The combined processes of heat conduction in a solid plate and of heat transfer within an adjoining boundary layer was analyzed [21C]. The results [23C] of an analysis of heat transfer from a melting flat surface to a forced convection laminary boundary layer were compared with experiments and were found to depend on the Prandtl and Kutateladze numbers.

Analyses were also performed for various unsteady situations. A calculation for steady flow and a step change in surface temperature of a wall near a two-dimensional stagnation point [17C] established conditions under which the quasi-steady approximation cannot be applied. Either constant surface temperature or a wall with adiabatic inner surface temperature was considered. A similar analysis [10C] studied the departure from transient heat conduction in a laminar boundary layer in wedge flow after a step change in wall temperature or in wall heat flux. The development of the three-dimensional thermal boundary layer around a body moving with constant acceleration [2C] and constant wall temperature was studied for a fluid with $Pr = 1$. A numerical solution [3C] of the boundary layer equations reveals acceleration and cooling effects in subsonic, supersonic, and hypersonic flow of a fluid with $Pr = 1$. In an extension of Lighthill's two-dimensional analysis, the thermal boundary layer near the stagnation point in a three-dimensional flow was studied [13C] for the condition that the upstream velocity oscillates in magnitude but not in direction.

The laminar boundary layer development during combustion on the surface of a disk rotating in free space and for a plate in Couette flow was analyzed [1C]. A general variational formulation [31C] of the coupled hydrodynamic, thermal, and diffusional multi-component boundary layers includes the effect of chemical reactions. Approximate solutions were obtained for the isothermal constant property flat plate at arbitrary Schmidt number. Stagnation point heat transfer from argon to a shock tube wall was measured [14C] with a thick calorimeter. The results agree with the analysis of Fay–Riddell.

Turbulent boundary layers

Finite difference solutions using mixing length relations describe the heat transfer in an incompressible turbulent boundary layer for an object with varying wall temperature in accelerating and decelerating flows [9C] and heat transfer in a non-equilibrium hypersonic boundary layer [7C]. The turbulent Prandtl number had to be given the value 1·5 to obtain agreement with experimental results for a hypersonic nozzle boundary layer. Experiments on asymptotic accelerated turbulent boundary layers showed that the depression in the Stanton number due to acceleration was increased by suction and suppressed by blowing [19C].

Measurements [8C] of heat transfer from a turbulent boundary layer to a cooled flat plate at $Ma = 6$ and $Re = 10^7$ were found to agree best with analytic results obtained by the Spalding–Chi method. The transition Reynolds number increased with cooling up to 60 per cent. The local heat transfer on a cylinder in longitudinal flow (at $10^5 < Re < 5 \cdot 10^7$, $1 < T_s/T_w < 4$) was found experimentally to increase with the ratio (0–8) of boundary layer thickness δ to cylinder radius r [29C]. The following equation was found to describe the results

$$St = 0.183 (\log Re_x)^{-2.45} (T_s/T_w)^{-0.25} (1 + \delta/r)^{0.14}.$$

The effect of stream turbulence on heat transfer from a cylinder in longitudinal flow was studied [28C] in the same Reynolds number range. Correlations for skin friction and heat transfer were summarized for hypersonic flow over cooled flat plates, cones, and wind tunnel walls for Mach numbers between 5 and 7.4 and for a temperature ratio between 0.1 and 0.6 [16C]. The boundary layer energy thickness was found to be the important parameter for the local heat flux.

Boundary layer velocity profiles could be approximated [18C] by the relation $\delta \sim y^{1/N}$ for varying Reynolds numbers, for Mach numbers up to 20, and for a wall to total stream temperature ratio from 0.12 to 1.35 with the parameter N expressed as a function of Reynolds number based on enthalpy thickness. The relation between the total-temperature and the velocity profiles measured [4C] in an accelerating turbulent boundary layer was found to differ from Crocco's relationship. Turbulent diffusivities for heat and mass transfer obtained by measuring the disturbance caused by thin wires [12C] compared well with analytic predictions by Bory and Taylor. On the basis of previously published velocity and temperature profiles, the turbulent Prandtl number was found [26C] to have values larger than 1 in the inner region and smaller than 1 in the outer region of a turbulent air boundary layer with little effect of suction or blowing. The effect of wall cooling [5C] and of stream turbulence [30C] on laminarization of a turbulent boundary layer was studied and the critical value of the laminarization parameter $[(v_e/u_e^2)(du_e/dx)]$ was established to have values between 1 and 4.4×10^{-6}.

Experiments [22C] clarified optimum conditions for impingement cooling of concave surfaces with a row of circular air jets. Impingement cooling was also investigated [20C] for a square array of round air jets impinging perpendicularly on a flat surface with Reynolds numbers based on jet diameter between 300 and 3×10^4.

FLOW WITH SEPARATED REGIONS

Single bodies

For turbulent separated flows at large Schmidt numbers, the mass transfer coefficient is proportional to (diffusion coefficient)$^{3/4}$ and (freestream velocity)$^{2/3}$ [38D]. Pei [5D, 34D] summarizes eight separate investigations on the effects of tunnel blockage and support on the heat transfer from spheres. The local heat transfer of ventilated, rough, spherical particles interests cloud physicists trying to understand the growth of knobby hailstones [23D]. A mechanism is proposed for the heat transfer from the rear of cylinders in crossflow. Heat penetrates into the eddy during the time the eddy is attached; the eddy sheds, and the cycle is repeated. The predictions [41D] are within a factor of two of the experimental data over the Reynolds number range $40 < Re < 2 \times 10^5$. Eddy shedding frequencies were measured [32D] in cross flow for air streams of different turbulence intensities and scales. The Strouhal number was found to remain constant at 0.130. Hinze showed that for circular cylinders, a condition of resonance occurs between the energy contained in eddies in the freestream and the shedding frequency. It appears [31D] that for spheres, the resonance hypothesis must be rejected.

The supersonic separated boundary layer is very sensitive to slot suction [2D]. Removal of a small percentage of the boundary layer mass defect is sufficient to collapse the separation bubble. Boundary layer "blow-off" injection rates are tabulated [24D] for non-Newtonian fluids on flat plates. The flow beyond an abrupt expansion in a circular channel shows considerable enhancement [46D] (over the fully developed value) of the average heat transfer in the separated region. Riley and Stewartson [36D] study the four regions of trailing edge flows for slender aerodynamic shapes which terminate in either a cusp or a wedge. Qualitative criteria are given for inhibition of separation. In a related paper [13D], El Assar gives a finite difference solution for the laminar wake behind a plate. Waldrop [42D] asserts that a Lax–Wendroff time-dependent, finite-difference, numerical scheme is the most desirable technique for computing three-dimensional base re-circulation flows. Fletcher [15D] correlates a large fraction of available data on base heat transfer in axisymmetric supersonic flow. R. Crane [9D] presents a survey of hypersonic near-wake studies. The problem of transition to turbulence in supersonic and hypersonic wakes occupies a prominent position in the study of free shear flows. Transition in the wake of a wind tunnel model is promoted [10D] when the body is cooled below the flow stagnation temperature, while body heating delays transition by factors up to 3·5. Fox *et al.* [16D] presents a review of problems in the nonreacting turbulent far wake.

A reference density criteria was developed in [44D] which permits prediction of the effects of molecular weight and other gas properties on the rate of mixing of dissimilar supersonic gas streams. For outer to inner stream velocity ratios greater than 26, a circulating toroidal vortex is established in the initial region of coaxial jets which enhances mixing [37D]. The appearance of two off-axis peaks in scattered light intensity measurements for condensation in carbon dioxide jet plumes led Beylich [3D] to give caution warnings about extending one-dimensional results to a two-dimensional flow field.

Jet momentum, not jet mass, is found [8D] to be the main determinant of the observed jet effects on the flow field generated by secondary injection of a gas normal to a supersonic stream. Velocity, turbulence intensity, and temperature profiles are presented [35D] for the interaction region of heated secondary jet flows with injection angles of 35° and 90° to the mainstream.

Arrays of two-dimensional impingement jets directed normal to a surface area are used for increasing the process rates. Sherwood numbers at the stagnation point of an impinging jet are twice those predicted by theory for a jet turbulence intensity of 20 per cent [27D]. Heat flux data for a jet penetrating into a blind passage in the shape of a parabolic concave area are applicable to thermal cooling of turbine blades [11D].

Packed and fluidized beds

Time-dependent fluctuations occurring at the mouth of triangular-shaped cavities may excite acoustic oscillations [40D]. Heat transfer coefficients are 65 per cent larger than the quasi-steady state value during the initial moments after inserting thin metallic spheres into a stream of liquid [28D]. Heat transferred from thin wires in laminar annular flow is 7–20-fold higher than calculated for fully developed laminar pipe flow [4D]. The effects of helical flow promoting inserts on boiling pressure drop is correlated for water and alkali metals at low pressures [39D]. Average heat transfer for circular and square cylinders are summarized [7D] for a high turbulence level nitrogen jet issuing from a 40 kW d.c. plasma torch.

Two papers, [33D] and [45D], deal with diffusion and flow of gases in porous solids. Jain [22D] analyzes unsteady spherical flow of ideal gases through a porous medium with pressure-dependent permeability. An analysis is given for predicting the thermal conductivity of heterogeneous mixtures that is shown to predict k within 18·2 per cent for suspensions, 9·5 per cent for emulsions, and 9·9 per cent for porous materials [6D, 20D]. By approximation of the radial profile in a fixed bed reactor [30D], a radial lumped parameter heat transfer coefficient has been obtained which enables a one-dimensional computational model to be used. It is possible to monitor the calculation of concentration and temperature profiles in a fixed bed reactor to ascertain whether the conditions represent multiple states and, therefore, non-feasible operating conditions [29D].

A mathematical model of a packed bed reactor is developed to include radial and axial diffusion within the reactor as well as film and pore resistances to both heat and mass flows [14D].

Two stationary methods for determining the thermal conductivity of porous insulating materials are described [17D]. The effective thermal conductivities of a number of different packings contained in a reactor tube is correlated in [1D]. The random loose porosity of a fixed bed provides a datum for correlating the flow through denser beds and for predicting minimum fluidization velocity [12D], while the large heat transfer rates in gas fluidized beds is the most significant advantage of the fluidization process [26D]. A correlation [18D] of the heat transfer rates in which the particulate bed is equal to or less than required for incipient fluidization is also useful. Related mass transfer studies for single particles, in fixed beds, and in fluidized beds are summarized in [43D].

A specially designed spherical probe reveals the presence of zones with different heat transfer behavior in spouting beds [25D]. Because fluidized beds have many properties analogous to liquids, it is common to assign viscosities to fluidized beds. Apparent shear viscosities have been estimated using the shape of a spherical cap result in values between 4 and 13 poise, in agreement with experiment [19D]. A Colburn *j*-factor type correlation of heat transfer in liquid fluidized beds accounts for the maximum heat transfer coefficient (h) at a given porosity and the variation of h with particle size and density [21D].

TRANSFER MECHANISMS

A dielectric fluid heated from above becomes unstable when a vertical alternating electrical field is applied. The analysis [17E] of this effect has been checked by the trend of measured Nusselt numbers. Heat transfer measurements [11E] at $Re = 3 \times 10^6$–8×10^6 with argon, air or helium injection through the porous surface of a 5° half-angle cone into an air boundary layer established that the transition Reynolds number decreases considerably with injection. The following relationship, derived from experiments, describes the effect of cooling on transition Reynolds number of a boundary layer [1E]. $Re_x = (T_w/T_e)^{-2\cdot3}\, Re_{x,\,\mathrm{iso}}$. Hot wire measurements [10E] on a swirling free jet established that the turbulence intensity is largest at the rim of the jet and in the layer separating the forward and reverse flows. A linear relationship between turbulent shear stress and turbulent kinetic energy is well supported by experiments for many flow regions [5E]. The proportionality constant is approximately 0·3. Turbulent Prandtl and Schmidt numbers were found by the spreading of a point mass source [4E] to be independent of Re but different in flow through a pipe and between parallel plates. Root-mean-square values of density, velocity, and temperature were found [6E] essentially independent of Mach number when properly normalized. Measurements [2E] in a cooled turbulent boundary layer found time-averaged velocity and temperature profiles to be in fair agreement with an analysis using mixing length and Coles transformation theories. Taylor–Goertler vortices increase the time-mean Nusselt number significantly according to experiments on a concave wall [12E]. A theory [16E] describes the near wall region of a turbulent flow as determined by a succession of laminar motions with short path lengths and applies the theory to pipe flow and flow near a separation point.

A computer code for coaxial free jets has been modified [14E] for other flows. Heat transfer in turbulent forced convection of a near-critical fluid is described by a penetration model [3E] which adds a boiling-like process to the normal transfer modes. Bradshaw's method to calculate turbulent boundary layers is simplified [13E] by the use of integral equations with a two parameter family of profiles. Differential equations for the turbulent kinetic energy and for a turbulent length parameter together with the time averaged Navier–Stokes equations constitute a closed system for the analysis of turbulent flows. The constants in the first two equations have been determined [15E] by a match of the results of such an analysis with experimental data for free jets and shear layers. The numerical values agree well for the investigated flows except for the round jet. The reason for this may be the fact that turbulent exchange occurs over finite distances. As another consequence, the shear and the time averaged velocity gradient not to vanish simultaneously in some flow situations. It was proposed [8E] to consider this in an analysis by adding a second order term to the equation describing turbulent shear.

$$\tau = 0{\cdot}4\rho k^{\frac{1}{2}} l \left[\frac{\mathrm{d}u}{\mathrm{d}y} + \frac{l}{2}\frac{\mathrm{d}l}{\mathrm{d}y}\frac{\mathrm{d}u^2}{\mathrm{d}y^2}\right]$$

(k turbulent energy, l turbulent length parameter).

Multi-point, multi-time velocity correlations describing the decay of homogeneous turbulence were studied [7E] following Deissler's approach. The propagation velocity of the rear-end of turbulent slugs in transition pipe flow was studied experimentally [9E] and compared with a theory.

NATURAL CONVECTION

Interest continues in natural convection within enclosures. Calculations included predictions of stability for a horizontal fluid layer heated from below and enclosed in a rectangular region [5F], and for horizontal layers of non-Newtonian fluid heated from below [61F], and the effects of gravity and surface temperature gradients on stability of fluid layers with initially parabolic temperature profiles [14F]. A simplified analysis permits extension of earlier stability calculations to natural convection within an inclined channel [30F]. The stability of fluids with non-linear density variations (with temperature) has been examined [1F]. Natural convection in enclosed porous media with rectangular boundaries has been analyzed [8F]. A linear perturbation analysis is used to study convection in finite right circular cylinders [6F].

An analysis [9F] indicates the stability and flow fields close to the stability condition emits in a circular cylinder heated from below. Radiative transfer in an absorbing, emitting medium stabilizes a horizontal fluid layer heated from below [12F]. Two-dimensional finite amplitude calculations for an infinite Prandtl number fluid show the effect of initial conditions at the lateral boundaries on convection [18F].

The initial flow patterns at the onset of convection in a horizontal fluid layer heated from below are found to be very dependent on property variation with temperature [56F]. Flow patterns have been observed in a circular cylindrical geometry immediately above the critical Rayleigh number for fluids with temperature dependent properties [25F]. Visual observations and measurement of some temperature and velocity profiles have been reported at low to moderate Rayleigh numbers [33F]. Cylindrical flow patterns were observed in a horizontal fluid layer which was non-uniformly heated from above [36F]. Experiments using volume-energy sources within a closed vertical circular cylinder include measurement of velocity and temperature distributions [39F].

Experiments on different liquids in natural convection between concentric spheres show the existence of various flow regimes [52F]. Computations predict the heat transfer in a rectangular cavity heated on one side and cooled on the other [43F]. Effects of vibrations on natural convection in a vertical rectangular cylinder have been studied [17F]. An empirical correlation is obtained [26F] for transient free convection in a revolving tube.

The onset of convection in a fluid layer above a transiently heated horizontal plate has been studied [45F]. Another transient study [24F] examines free convection heat transfer in mercury in a vertical rectangular channel.

An analysis [22F] indicates the spectrum of convective instabilities in a vertical channel with permeable boundaries. Flow in the entrance region for natural convection in a vertical circular tube has been analyzed [29F]. The distortion produced by natural convection on a non-Newtonian flow in a vertical pipe has been predicted [15F].

A number of works examine combined natural and forced convection. In one, the effect of thermal boundary conditions on fully developed laminar flow in horizontal tubes is analyzed [42F]. In another, the secondary flow induced by buoyancy in a parallel plate channel heated from below is examined [41F]. A computational and experimental study of the secondary flow field produced in a heated horizontal tube has been presented [54F]. Combined natural and forced convection has been examined with approximations to obtain similarity solutions [59F]. Different boundary conditions are used [27F] to study the effect of buoyancy on forced convection in vertical polygonal ducts. A numerical solution gives the entrance region flow in a vertical tube with combined natural and forced convection [37F].

The deviation of the natural convection heat transfer coefficient on a vertical circular cylinder from that which would be encountered on a vertical plate has been calculated [20F]. Detailed experiments [19F] have been carried out on laminar and turbulent natural convection heat transfer from a vertical circular cylinder to various liquids. Another study [40F] of laminar natural convection on vertical cylinders examines the flow on very thin cylinders; only a weak dependence of Nusselt number on Rayleigh number is found.

Combined forced and natural convection flow on vertical surfaces has been analyzed using a local similarity model [34F]. Laminar natural convection, including coupling of the conduction through the wall, has been studied on a vertical plate [63F]. An analysis using the actual property variations of water gives fair agreement with available experimental results for natural convection heat transfer in the supercritical region [44F].

Several transient studies on natural convection from vertical plates have been performed. One included a vigorous transient including transition to turbulent flow by waves propagating from the leading edge [38F]. Another [47F] analyzes the transient laminar natural convection at Prandtl number of unity. A one-dimensional transient analysis is used to determine the effect of buoyancy on the formation of a solid deposit freezing onto a vertical surface [32F]. An analysis of transient free convection on two-dimensional or axisymmetric bodies has appeared [16F].

Interest has been extended to natural convection from vertical surfaces on which mass transfer also occurs. A laminar flow analysis for various geometries with simultaneous heat and mass transfer has appeared [51F]. The heat and mass transfer in a binary turbulent boundary layer has been examined [3F]. A porous vertical wall has been studied with natural convection and independent suction [31F]. An experimental study was made [2F] of combined forced and natural convection with simultaneous heat and mass transfer on a vertical plate.

Inclined surfaces have been studied. Instability on such plates, as reported in one work [35F] is characterized at large angles of inclination by longitudinal vortices. Another study [23F] reports separation of the flow before transition to turbulence occurs.

Several experiments report on natural convection near finite horizontal plates. An integral approach is used [13F] to get the Nusselt number on a cooled plate facing upwards. A cooled plate facing upwards has also been studied treating the velocity field as a stagnation flow [10F]. One study reports boundary layer flow on a heated horizontal plate facing downwards [55F]. Another study [49F] contradicts this finding of no boundary layer flow on a heated horizontal strip facing downwards. Dif-

FIG. 1. Photographs of thermals rising from a heated horizontal surface [57F].

ferent flow regimes are observed [62F] above a horizontal surface with mass transfer simulating heating.

In several studies, heat transfer from horizontal cylinders is measured. In one [48F], shadowgraph observations indicate the effects of horizontal and vertical sound fields. Combined natural and forced convection (in an aiding flow) heat transfer on a cylinder have been measured [46F]. Instantaneous measurements are reported [58F] of the heat transfer from an oscillating wire in natural convection using a photocell. A thin wire has been used [4F] to study natural convection to a reacting gas.

An interferometric measurement of laminar natural convection from a horizontal line source has been reported [21F]. Other experiments on this flow phenomena have been performed [53F] in a number of different liquids. An analysis [50F] of a buoyant, two-dimensional laminar vertical jet indicates that the maximum velocity first decreases and then increases with height. A turbulent buoyant plume analysis [60F] is used to predict natural convection above fires. Buoyant thermals rising from a heated horizontal plate situated in water were made visible by an electrochemical flow visualization technique [57F]; see Fig. 1. Measurements of the frequency at which the thermals were generated agreed reasonably well with an analytical model proposed by L. N. Howard.

An optimization has been performed [7F] for the natural convection heat transfer from vertical rectangular fin arrays. A simplified correlation is obtained in a study for the optimal arrangement of rectangular fins on horizontal surfaces [28F]. Natural convection in air between a vee-corrugated plate and a flat plate approximately fits horizontal fluid layer heat-transfer correlations [11F].

CONVECTION FROM ROTATING SURFACES

Experiments [1G, 5G] on a shrouded rotating disk with freely induced and forced cooling established average Nusselt numbers with values between 50 and 6000 in the Reynolds number range from 2×10^4 to 4×10^6 with a Reynolds number based on disk radius and circumferential velocity. Mass transfer experiments [4G] using naphthalene and the same system as above studied the effect of clearance between disk and shroud at Reynolds numbers around 5×10^3. The equations for the thermal boundary layer at a rotating axisymmetric surface were solved [2G] using Dorodnitsyn's transformation. Experimental information is reported [3G] for the heat transfer in a rotating heat pipe. With methanol as coolant, the temperature difference between the hot and cold ends could be reduced to one-half the value for the stationary pipe. This device is proposed for the cooling of the rotor of an electric motor.

COMBINED HEAT AND MASS TRANSFER

Three studies [11H–13H] are reported in the Russian literature on various aspects of film cooling. A simplified analysis [11H] predicts film cooling effectiveness on a flat surface downstream of a porous strip through which mass is being added. Previous analyses have been presented by a number of investigators. Film cooling by air injection through a slot normal to the surface was studied over a range of parameters [13H]. The film cooling effectiveness is much less than that provided by tangential injection, in particular, when the blowing parameter is greater than 0·3. When film cooling a rotating cylinder up to a moderate rotation speed, the protection is quantitatively similar to that without rotation [12H].

Another film cooling study [8H] at subsonic flow utilizes tangential injection. Variation of the secondary flow distribution at the point of injection is found to have a significant effect on film cooling performance when the blowing parameter approaches unity. Experiments on a cooled gas turbine combustor [1H] indicate relatively close agreement with conventional film cooling correlations.

The use of discrete holes to provide entrance of a secondary flow has been studied [6H]; the film cooling is drastically reduced from the case of slot injection, particularly at large blowing rates when the jets of secondary fluid penetrate into the mainstream away from the solid surface.

Film cooling with tangential injection into a Mach 6 turbulent boundary layer is found to give significantly better protection than found in low speed flow [2H]. Quantitatively, however, these results do not agree well with earlier experimental studies of high-speed flow. The reduction of heat transfer on a slender cone in hypersonic (Mach 12–17) flow has been measured using combined film cooling near the nose and transpiration cooling along the surface [15H]. Transpiration cooling of a blunted cone in a Mach 13·4 stream was studied using various molecular weight injectants [10H]. With lighter gases, the heat transfer reduction is greater the lighter the gas at the same mass flow rate of secondary fluid. Freons of different but relatively large molecular weight each give about the same reduction in heat transfer. The coupled laminar boundary layer equations are solved [16H] to determine the effect of upstream mass injection on downstream heat transfer along a surface exposed to a Mach 2 airstream. An analysis [4H] shows the effect of massive distributed blowing on a supersonic turbulent boundary layer. Another analysis [3H] of the compressible turbulent boundary layer with mass addition shows that there can be significant distortion of the flow field. The importance of radiation in determining the phenomena associated with a laminar ablating air–teflon boundary layer at temperatures of 3000–6000K has been demonstrated experimentally and analytically [7H]. Formation of the variable-property laminar-boundary layer equation in terms of mole fraction eased the solution of these equations with simultaneous energy and mass transfer [9H].

A study of liquid film cooling [5H] indicates that the entrainment mass transfer can be several times larger than evaporation losses. The heat and mass transfer, when injecting liquid hexane and ethyl alcohol into an oxygen mainstream, was studied analytically and experimentally [14H].

CHANGE OF PHASE

Boiling

Lately, Freons have come into extended use as the working media in thermal power facilities [16J]. Boiling heat transfer to Freons C318 and 21 are compared with nine different empirical correlations [17J]. Two papers, [43J and 45J], deal with the effects of reduced gravity on nucleate boiling including boiling studies in flat, inclined containers. In the study of acoustic phenomena arising in boiling, interference of individual components of the noise spectrum can result in appreciable errors [41J]. The large sound pressure level observed [7J] during transition boiling is attributed to the rapid evaporation rate of liquid droplets coming into direct contact with the boiling surface and also the high frequency of such contacts (quenching). Heat transfer in nucleate pool boiling of dilute polymer solutions show increases as great as 250 over pure water. Different hydrodynamic patterns were observed [47J]. Pool boiling heat transfer to liquid helium is greatly increased by treating the surface [12J]. The phenomenon is useful in the construction of cryostatically stabilized magnets. A modified form of the Rohsenow correlation has been proposed which takes into account the influence of the grain size of the surface metal [60J]. Pool boiling from large arrays of artificial nucleation sites is a useful tool [32J] for evaluating effects of active site density and bubble emission frequency—two major variables which affect the liquid velocity near the heating surface. Measurements performed by means of an optical method show that for a given system of liquid and heating surface, there exists no specific value of bubble frequency and measured frequencies are distributed randomly about the average [81J]. The loss of inert gas from surface cavities during incipient boiling tests of liquid alkali metals can mask other phenomena [78J]. Kippenhan and Tegeler [42J] describe a procedure for the measurement of dynamic surface tension in the single bubble region. The concept of a static contact angle causes erroneous results in the analysis of boiling heat transfer. The dynamic contact angle was found to vary sharply as a bubble grows [4J]. Mikic, Rohsenow and Griffith [58J] develop a single relation for bubble growth in a uniformly superheated liquid applicable in the entire range of the growth curve. Bubbles can be stabilized on a vertically vibrating column. Experiments on the effect of bubble stabilization on the rate of pool boiling heat transfer show that with the liquid and heating surface vibrating as a unit, a decrease of up to 12 per cent is found [24J] in the temperature difference necessary for a given heat flux. Experimental and analytical results are given for the response of a vapor bubble to a sinusoidal pressure pulsation [36J].

Growth constants of the initial vapor bubble growth on a horizontal heated wall are compared with five different models and found to correspond most closely with a model which postulates a "thick" microlayer of constant thickness [77J]. The extremely rapid surface temperature fluctuations (up to 30°F/ms) measured during steady state boiling are due [72J] to the evaporation of the microlayer of a bubble passing over the thermocouple. In [48J], the mechanism of micro-liquid layer formation is investigated using a flattened air bubble generated between parallel disks. It is concluded that a liquid layer put between a bubble and a solid surface is subject to a positional change in pressure due to a surface tension such that the liquid layer flows against the viscous force leaving a micro-liquid layer behind with a thickness of the order of microns. The thickness of the microlayer is inversely proportional to the square root of the Reynolds number based on bubble radius and growth rate [46J]. In the early stages of bubble growth, the microlayer influences bubble growth through the increase in the liquid-vapor interfacial area. In the advanced stage, a bubble with film evaporation and subsequent condensation is the important mechanism for bubble growth and accounts for nearly all of the heat transfer [70J, 71J].

Gas injection through the wall of a porous heater into water can promote heat transfer from the surface to such an extent that the heating surface operates at a lower temperature than that of the bulk fluid [22J].

Hausen extends the Fitz equation for the calculation of nucleate boiling up to the critical region depending only on the reduced pressure p/p_{cr} [31J]. The heat transfer coefficient at conditions very close to the critical point is very large. Abadzic and Goldstein [1J] give correlations for film boiling of carbon dioxide in the subcritical region and free convection in the supercritical region.

The burnout heat flux in rectangular and triangular channels is appreciably lower than in a circular pipe [14J]. Transient DNB behavior of rod bundles can be predicted using steady state DNB data from the same geometry and under the same local fluid conditions [13J]. Estimates are presented of the effects of several geometric characteristics of multirod bundles on q_{cr} in longitudinal flow [88J]. Experimental data point to the conclusion that the relation between the critical heat flux and the main process variables can be different for small and large subcooling. Glushchenko gives a design relation for determining q_{cr} for large subcooling [25J, 26J]. About 440 original observations of q_{cr} on horizontal cylinders are presented for a range of sizes, gravities, reduced pressures and boiled liquids that are correlated within 20 per cent [83J]. Bubbles rising above a heater of finite size drag the surrounding fluid and exert a secondary flow about the heater. This induced-convection, which affects q_{cr}, is magnified by gravity [53J]. Dryout is initiated by nucleation or thermocapillary forces in a liquid film or by film starvation. In [57J], these forces are evaluated for typical dryout conditions. For dry patch stability, the shear force must be equal to the net surface force. Two types of dryout were found in horizontal channels which limit q_{cr} [38J]. Both aperiodic and vibrational instabilities reduce the flow in parallel, small-diameter, steam generating channels. This may be one of the causes of the observed reduction in q_{cr} [65J].

Although quenching is a major mechanism for heat exchange in transition boiling (≈ 50 per cent), nucleate boiling is found to be responsible for the rapid increase in q as ΔT is decreased [6J]. The heat capacity of the heating wall does not enter into the condition of heat transfer stability in transition boiling [49J]. The transient calorimeter technique is proved to be generally unsuitable for obtaining reliable boiling curve information [9J]. Unless surface conditions are strictly controlled, the transition and nucleate boiling regions are greatly distorted.

Minimum film-boiling data are presented for several pure light hydrocarbons and compared with the widely referenced minimum film-boiling correlations of Berenson [75J]. [63J] investigates minimum heat flux at near critical pressures. For the case of water spheres on a liquid nitrogen surface (in Leidenfrost boiling), the predicted freezing times compare favorably with measurements [33J].

The presence of appreciable surface radiation for laminar film boiling in several boundary layer flows results in an increase in heat transfer and a decrease in skin friction [95J]. A significant low gravity transition is identified and explained (wave-collapse to bubble merger) in the vapor removal mechanism during film boiling on horizontal cylinders [54J, 67J]. Cochran [15J] describes the properties of a bubble boundary layer found in forced convection boiling near inception in zero gravity.

Condensation

Rohsenow reviews an extensive list of solved problems in film condensation [73J]. Experiments confirm with new certainty the unity of the evaporation and condensation coefficients of common liquids [56J]. Measurements of liquid metal condensation and evaporation coefficients suggest that as the system becomes successively cleaner, the magnitudes of the coefficients rise toward unity. The pressure dependence reported by others is due to experimental error [92J]. The critical supersaturation model (CSM) provides a closed-form expression for condensation-enhanced vaporization rates in real boundary layers in terms of a single function which incorporates condensation kinetics [19J]. One aspect of the condensation problem that is now receiving attention is the condensation of vapors of immiscible liquids [84J]. [64J] suggests that in filmwise condensation of mixed gases in a vertical column, the heat transfer coefficient should be calculated by the same equations as for condensation of a pure vapor. Other papers referring to the presence of non-condensable gases disagree with this conclusion [85J, 86J]. Laminar flow condensation heat flux measurements of steam with small concentrations of air are 20 per cent above the Minkowycz analysis because of forced vapor flow [79J]. Krupiczka [51J] discusses dropwise condensation for laminar natural convection with both large and small vapor-flux density toward the wall. Non-isothermal boundary conditions influence laminar film condensation to a maximum extent [61J]. Uniform suction causes a substantial increase in heat transfer and laminar film condensation rate on vertical porous walls [94J]. In the case of steam–water film condensation near a stagnation point on a general curved surface, Poots and Miles [68J] have established that the Nusselt–Voskresenskiy method is in error by at most 5 per cent. Increases in heat transfer to 400 per cent were obtained by condensing steam on a vertical cylinder rotating at up to 2700 rpm [62J]. The increase is attributed to the film being thrown off due to the centrifugal forces acting on it. The condensation of Freon-114 in the presence of a non-uniform 60 cycle electric field increased as high as ten times as a result of the controllable body forces produced [35J].

Unlike condensation in single component systems, the two component, three-phase system is characterized by condensate accumulation within the confines of a collapsing bubble which hinders interfacial mobility [37J, 59J].

Thermocapillary flow (fluid flow induced by surface tension forces) does not contribute over a few per cent to the heat transfer in dropwise condensation of water [55J]. Two-phase annular flow liquid droplet deposition studies indicate that the mean-free path is proportional to droplet diameter [20J]. Heat transfer data for individual water droplets impinging upon a heated surface [66J] show that the approach velocity is the dominant variable and that surface temperature has little effect in the non-wetting regime.

Two-phase flow

Kalinin [40J] rederives the equations of motion for two-phase flow with mass transfer between the phases. In [30J] a study of steady-state heat transfer in partially liquid-filled porous media was used to test the validity of linear force-flux equations. A variational principle of maximum momentum flux is formulated [82J] for two-phase flows and is well verified in metal vapor–liquid systems. A new concept of a sequence of plots is used for the separation of flow regimes in two-phase flow [5J]. The empirical correlations are based on extensive tabulations of flow-type data from the AGA–API Data Bank. Techniques of computational fluid mechanics are proposed [23J] for a flow situation in which three fluid effects interact; viscosity, inertia, and surface tension; a flow in which a series of gas bubbles moves along the centerline of a variable area channel. [18J] gives results of six reports on two-phase flow through porous beds, screens, and membranes in low gravity environments while a related paper [34J] discusses orifices and nozzles. A choking prediction for flashing flow in a sharp-edged discharge line is developed from a free streamline analysis [28J]. An explanation is given [52J] for pressure fluctuations that have been observed in discharging saturated systems. Filippov [21J] discusses the determination of the degree of nonequilibrium of the expansion of two-phase media. Two papers [20J, 27J] deal with gas suspensions and point out that the presence of solid particles in a gas stream greatly intensifies the exchange of heat transfer with a surface. In [76J] the selection of the gas temperature as the reference temperature in calculating the heat transfer coefficient to particle-laden flow is substantiated and the effects of the particles on thermocouple output are estimated. Stepanov [80J] gives relations for estimating upper and lower bounds on the thermal conductivity of two-phase systems with arbitrary structure. Three papers [29J, 39J, 89J] deal with the boiling of binary mixtures with and without chemical reaction. [93J] describes boiling of liquids at very low pressures. A method for calculating wet steam condensation processes based on the Frenkel formula for the nucleation rate is in agreement with supersonic nozzle data [44J]. The statement that the rate of water evaporation decreases as the humidity increases should be revised [90J] since the rate of evaporation of water has an inversion point with respect to air. Design equations are presented based on data for evaporation rates of water from inaccessible places such as slots, pockets, and screw threads inside closed vessels under rarefied conditions [8J]. Bressler and Wyatt [11J] investigated the effects which capillary grooves of different shape and size had with respect to the wetting of a solid surface. Thin axial fins on the inside of a tube markedly enhanced the evaporative heat transfer of thin water films [87J]. Ackerman [2J] summarizes extensive data in smooth and ribbed tubes on supercritical heat transfer in the pseudocritical temperature region (temperature at which density gradient and specific heat attain maximum values). Two papers [3J, 74J] extend methods of calculation of void fraction in the subcooled and bulk boiling regions of a heated channel to include slip ratios other than unity Walford [91J] describes transient heat transfer from a hot nickel sphere moving through water. [50J] presents heat transfer data on the spheroidal state inception temperature of droplets on a heated surface. Rabinovich [69J] describes convective drying of fine disperse material in an agitated bed with the evaporated moisture and the drying agent moving in opposite directions.

RADIATION

The monochromatic and total normal emittance of diffusely reflecting cylindrical cavities has been calculated [55K]. It was found that the normal emittance is larger than the hemispherical emittance for ratios of the depth to the radius of the cavity larger than one. A highly reflective specular cone constitutes a good passive radiant cooler for instruments when it is viewing cold space [1K]. Radiant transfer between grooved surfaces was investigated analytically [28K] and experimentally [2K]. Grooving of the surfaces may descrease heat transfer up to 40 per cent. Diffuse, specular, and diffuse-specular analytic results for two parallel strips were compared [19K, 58K] with experimental data using steel plates with and without gold plating. A group of papers presents the analysis for thick [18K] and thin [3K] films of a non-conducting dielectric between metal surfaces and experiments [17K] which find some large discrepancies with theory at cryogenic temperatures. The Monte-Carlo method applied to the calculation of radiant heat transfer has been discussed [60K] and the results of a least-squares technique have been compared with numerical solutions for two plates oriented parallel and normal to each other [54K]. Eddington's approximation was used [9K] to analyze steady and transient heat transfer by combined radiation and conduction in a medium bounded by two coaxial cylindrical surfaces. A new approach [23K] to the calculation of configuration factors for radiation from spheres and cylinders shows that for certain shapes the angle factors are independent of the distribution law of emission.

The total emissivity of austenitic steels used in breeder reactors was measured [38K] for temperatures from 200 to 700C, for various surface treatment and oxidation stages. From experimental results, it is concluded [59K] that the spectral emissivity of refractory metals at 0·65 μm varies exponentially with temperature. Freeze-dried beef has total emittance values between 0·7 and 0·85 [45K]. The variation of the emittance with wave length is moderate. An oxide layer of Al_2O_3 on an aluminum substrate has total emittance values from 0·15 to 0·92 for a thickness from 1·2 to 86·4 μm, an oxide film of CuO on a copper substrate has emittance values from 0·09 to 0·81 for layer thicknesses from 1·2 to 5·6 μm [5K]. A precision method [34K] to measure specular reflectance of thin optical coatings at 10·6 μm wave length uses a CO_2 laser and achieves an accuracy to 1 in 10000 for coatings with more than 99·9 per cent reflectivity.

The effects of radiative heat transfer between surfaces can be substantially increased by interleaving fins [24K].

Efforts continue to develop more sophisticated models which take the nongray nature of radiation in participating media into account and which provide better agreement between theoretical predictions and pertinent experiments. A more sophisticated model for nongray radiative transfer is introduced which, in principle, can accurately approximate any spectral distribution [15K]. A numerical solution for the radiant heat transfer in a plane parallel layer of gaseous CO_2 and H_2O and their equimolar mixtures shows that known solutions for gray radiation differ appreciably from this work which utilizes more exact expressions for the emissivity of the gases involved [16K]. In a study of nongray radiation heat transfer in a high-temperature, non-isothermal CO_2–N_2 mixture, the nongray nature of the gas is accounted for by a spectral evaluation of the radiative energy transfer, employing simple spectral absorption coefficients for the transport processes due to photoionization, free–free electron interactions, and molecular band transitions [4K]. Experimental and theoretical results of heat transfer studies in fully developed turbulent flow of a nongray radiating gas in a circular tube are in good agreement [26K]. The total band absorptance is used to include nongray effects for studying the radiative transport in a nongray cylindrical medium [25K]. A band absorptance formulation for nonisothermal gaseous radiation is shown to be in reasonable agreement with experimental data and other analytical predictions [7K].

Total radiation measurements for nitrogen, oxygen, and argon plasmas in the wavelength range from 2000 to 60000 Å and for temperatures from 9000 to 15000 K indicate that line radiation is of the same order of magnitude as the total continuum [36K]. An analysis of the radiative energy transfer within a hydrogen plasma shows that line radiation can have a significant effect on this transport for moderate pressures. At higher pressures, the lines become opaque and no longer contribute to the radiative transport process [44K].

The problem of radiant transfer in zones of boiler and furnace units is reduced to a closed system of two gray diffuse bodies by a selectively gray dust-laden or dust-free isothermal gas [35K].

Problems associated with simultaneous conduction and/or convection and radiation have been extensively studied. An analysis of the transient and steady heat transfer in a conducting, emitting, and absorbing medium reveals that for short time intervals emission is negligible in comparison with absorption, whereas for long time intervals it becomes important for a thin layer only near the hotter surface [8K]. A rigorous differential formulation for the transient energy transferred by simultaneous conduction and radiation in an absorbing, emitting and scattering medium lends itself more readily to different limiting and special cases [27K]. The nonlinearity of two-dimensional heat transfer in a conducting and radiating medium is not as severe as previously assumed [43K]. Typical results of an analysis for nongray radiation-conduction interaction in a radiating gas bounded by two gray infinite parallel plates are discussed with emphasis on the effect of surface emittance and approximate kernels [51K]. Studies of simultaneous conduction and radiation heat transfer in a planar layer of NH_3 disclose satisfactory agreement between experiment and theory [50K].

The normal mode expansion technique is used to obtain the radiation intensity in a conservative finite slab with an internal source and plane-parallel emitting boundaries [37K]. The unsteady interaction between a dominant radiation field and a flow field leads in the lowest order approximation to a radiative cooling process with an uncoupled flow, and an expansion in Boltzmann number then systematically introduces higher order effects [11K]. A characteristic approach is applied to various problems of radiative gasdynamics. Results show that a differential approximation predicts surface pressures and heat transfer rates accurately [20K]. The heat flux at and near the wall stemming from a radiating but non-viscous and non-conducting fluid flowing over a flat plate is derived from an exact solution of the equations describing the temperature distribution in this fluid [61K]. The interaction of radiation with convection is considered in an absorbing-emitting boundary layer of a nongray constant fluid flowing over a gray, diffuse, isothermal flat plate [42K].

The method of discrete ordinates applied to planar radiating flow yields a high degree of accuracy of the results and may be extended to multi-dimensional radiating flow [10K]. Results obtained from the application of a sampled-data model to the transient response of a distributed parameter system subject to simultaneous radiation and convection are in excellent agreement with results in the literature [22K]. It is shown that thermal radiation in the entrance region of a circular pipe carrying an absorbing fluid increases the heat transfer near the entrance by as much as a factor of four and reduces the thermal entrance length by a factor of ten [49K]. The effect of radiation on the enthalpy distribution and on the thickness of a laminar boundary layer is studied analytically [21K]. The effect of radiation on film boiling in a forced convection boundary layer flow manifests itself in an increase of the vapor temperature and of the heat conduction at the vapor–liquid interface while the heat conduction at the wall is at the same time reduced [39K].

Studies of radiation scattering for particle diameters of 0·106 and 0·530 μm at wavelengths of 0·436 μm and 0·546 μm and optical thicknesses from 0·25 to 3000 show excellent agreement between theory and experiment [31K]. Absorption and scattering of thermal radiation in a cloud of small, spherical aluminum oxide particles suspended in carbon tetrachloride and carbon disulphide is measured in a wavelength range from 2 to 11 μm [46K]. A new analytical method is proposed for determining generalized local and average angular emission factors for the exchange of radiation between bodies separated by absorbing and scattering media [56K]. The high efficiencies of heat exchangers and reactors operating with small particles in a homogeneous suspension are due to the quick heat exchange between gas and particles (in the order of 10^{-5}–10^{-4}) [12K].

Approximate analytical stagnation point solutions for inviscid radiating shock layers are presented for various limiting cases of the radiation involved [47K]. By considering the spectral aspect of radiative transfer, the influence of upstream absorption of the energy radiated from the inviscid stagnation region shock layer on the stagnation region is determined [41K]. Normal shock waves structured by nonequilibrium radiative and collisional ionization consist of a strong precursor, the embedded discontinuity, an inner collisional tail, and an outer radiative tail [13K].

A perturbation theory of non-isentropic flow with radiative heat transfer in supersonic steady flow demonstrates that radiative heat transfer reduces the strength of the shock [48K]. The asymptotic behavior of an inviscid radiating gas flow near the stagnation point of a blunt body in the weakly radiating and weakly absorbing limits is correctly described in this paper [33K]. An approximate computational scheme is delineated for calculating the radiating, inviscid flow field for a blunt body re-entering the earth's atmosphere [57K]. Calculations of the effect of radiation on hypersonic viscous flow at low densities show that nonequilibrium radiation influences flow field and heat transfer considerably [52K].

The specification of a general optically thin limit which is discussed in conjunction with the various Planck mean coefficients [14K] requires the optical depth to be small and a statement about the degree of radiative nonequilibrium.

Spectral absorption coefficients of water vapor are measured in the 1–8 μm range at temperatures from 575 to 1250 K for path lengths up to 1 m and at pressure levels up to 1 atm [29K]. An iterative solution of the radiative transfer equation is presented for the temperature and absorbing gas profiles of an atmosphere based on spectral and angular measurements of atmospheric radiance [53K]. Even invisible water aerosols show strong absorption and emission in the 8–13 μm atmospheric window [6K].

A computer method is suggested to calculate the heat transfer from flames and hot gases to the walls of a furnace [40K]. An experimental method for measuring the temperature and emittance of luminous flames in gas turbine combustors is proposed for chamber pressures from 2 to 7·5 atmospheres and for a turbine inlet temperature range from 900 to 1950°F [30K].

Visible radiation emitted from a plasma generated by hypervelocity impact of a projectile on a target (impact flash) reveals a submicrosecond pulse of continuum radiation and a slow-rising light pulse composed of the line radiation of neutral atoms [32K].

LIQUID METALS

Analytic solutions [1L] have been obtained for turbulent heat transfer to liquid metals flowing in concentric annuli. The effect of thermal development and of variable heat flux has been studied by starting with a step change in the wall temperature and then generalized using Duhamel's method. Deissler's expression for the turbulent diffusivity and a turbulent Prandtl number of one were used. Numerical computations [2L, 3L] established laminar flow and slug flow Nusselt numbers for in-line flow of a liquid metal through unbaffled rod bundles. Average heat transfer coefficients and circumferential wall temperature variations are reported and a maximum of the heat transfer coefficient was found at a value of 1·20 of the ratio of tube spacing to tube diameter.

Experiments on heat transfer to mercury flow in-line through a rod bundle [6L] established that local and average heat transfer coefficients decrease if a rod is displaced. Free convection and nucleate boiling heat transfer data for pool boiling of potassium [8L] and for sodium boiling in a vertical tube [7L] were reported with heat fluxes from (2 to 7) $\times$ 10^3 W/m^2, for vapor fractions up to 60 per cent, and vapor velocities to 460 m/s. A small quantity of inert gas introduced at the inlet insured annular flow. Experiments [9L] established Nusselt numbers for internally generated flow of sodium in rotating closed straight cylindrical channels on a rotor disk. Two papers [4L, 5L] report the results of analyses for laminar flow and slug flow through rod bundles with the goal to establish the effect of cladding of the rods. The thermal resistance of a stationary liquid metal interface containing gas cavities was analyzed [10L] and compared with test data.

LOW-DENSITY HEAT TRANSFER

A number of papers have been devoted to the study of heat transfer at low densities. A solution of the linearized Boltzmann equation (BGK-model) for a rarefied gas flow between two stationary parallel plates is in excellent agreement with solutions for the limiting case of free molecular flow [5M]. A new approach based on the BGK-model is proposed which can be applied to problems associated with nonlinear heat transfer between concentric cylinders [7M]. Based on the linearized BGK equation, variational principles for a rarefield gas flow past an arbitrary three-dimensional isolated body are applied to the case of constant wall temperature and to an adiabatic wall [6M].

An improved discrete ordinate approach involving the Willis integral iteration is checked by application to linearized cylindrical Couette flow. The results agree well with previous ones [8M].

More accurate Monte Carlo solutions of the Boltzmann equation are obtained for the pseudoshock and the heat transfer problems by using new techniques developed in this paper [10M]. The linearized form of the Boltzmann transport equation is applied to the flow of a rarefield gas between two parallel plates [9M].

An analysis is presented of the heat conduction problem of a rarefied gas in the slip regime confined between two concentric cylinders maintained at a small temperature difference [11M]. A thin film surface thermometer is used for heat flux measurements in hypersonic rarefied gas flows [1M].

The contribution of wall recombination to the heat transfer in a dissociated slip flow may be calculated from a simple equation derived in this paper [2M]. Thin wire Langmuir probe measurements in the transition and free-molecular flow regimes indicate that the measured electron temperature does not depend on the probe diameter or the fineness ratio [3M].

A direct thermal-to-pneumatic energy converter is proposed utilizing the principle of thermal transpiration through a porous membrane [4M].

MEASUREMENT TECHNIQUES

A report on thermoelectric measurement of low temperatures emphasizes the importance of calibrating individual thermocouples [17P]. Thermocouple errors due to transients have been calculated [10P]. A thermostat has been developed to aid in calibrating surface temperature transducers [20P]. A thin film (5–10 μm) thermocouple has been used to measure surface temperature [32P]. The error in temperature measurement using a surface-mounted thermocouple has been analyzed considering the thermocouple as a local heat sink [11P].

A high-speed optical pyrometer has been developed [8P] with a time constant less than a millisecond. Infra-red semi-conductor devices have been used for thermal analysis to 3000°C [1P]. Standards for radiation measurement of temperature have been reviewed [19P]. Statistical distribution of errors in pyrometry have been explained [16P]. Calculations have been made [33P] of the errors which may be introduced in optical pyrometry when individual optical elements are included.

A rugged shearing interferometer has been analyzed [14P]. A schlieren interferometer has been used to directly measure temperature gradients [30P]. A modified Michelson interferometer was developed [28P] for highly transient plasma diagnostics. A laser interferometer schlieren system has been used for high frequency gas density measurements [4P].

Possible use of the Mössbauer effect to measure temperature fields in solids has been examined [3P]. A transient technique has been developed [21P] for local measurement of surface heat flux. Measurement of velocity and temperature fluctuations can be combined to determine local turbulent heat flux [2P].

Radiative absorption and emission are found [22P] to significantly effect thermal conductivity measurements of some gases even at moderate (700 K) temperatures. Cyclic incident radiation to a surface is used [12P] to measure radiation properties from the surface.

A Preston tube has been used to measure wall shear stress at a free stream Mach number of 7 [13P]. A ball-type probe is found to be relatively accurate in measuring static pressure in a three-dimensional flow [29P].

The deviation from King's law for the heat loss from a hot film anemometer is determined in calibrating for low velocity measurement in a non-isothermal flow [34P]. Correction of hot-wire anemometer measurements in a turbulent boundary layer due to the proximity of the wall have been studied [26P]. The higher harmonics generated in a hot-wire anemometer have been simulated with an analog computer [5P]. Measurements [27P] in water demonstrate the wide applicability of hot-film probes for velocity determination. Large errors are found [31P] in measuring velocity with a hot-film anemometer in turbulent flow of viscoelastic fluids. Hot-wire measurements of fluid velocity have been accomplished in high temperature jets by putting the sensing wire into a cooled impact probe [24P].

Crossed light beams are used [7P] to measure turbulence properties of supersonic air jets. The refraction of two laser beams is studied to analyze atmospheric turbulence [6P]. Fraunhofer holograms of small spherical particles can be used to measure local fluid velocity [23P]. A pulsed ruby laser is used in a holographic interferometer for subsonic flow visualization [25P]. A high-frequency corona-discharge anemometer has been used to study subsonic turbulent flows [9P].

Flow visualization of liquid laminar boundary layers can be accomplished using a chemical coating which washes off into the flow [18P]. Precision volumetric and mass measurements of fluid flow rate have been reviewed [15P].

HEAT TRANSFER APPLICATIONS

Heat exchangers

The heat transfer and pressure drop performance of heat exchangers with various extended surfaces were investigated. Among these were studded tubes [1Q], plates with wire loop fins [17Q], and transversely finned tube bundles [3Q] for Reynolds numbers between 14000 and 50000. The effect of bypassing of the flow through the space between the tube bundle and shell of a heat exchanger is considerable [5Q], especially at small flow rates. An analysis [2Q] investigates the performance of co-current and counter-current heat exchangers with parabolic velocity profile in the fluid. The dynamics of heat exchangers subjected to simultaneous changes in flow rate and entrance temperature was analyzed [10Q, 11Q, 16Q]. Also investigated was the performance of a gaseous suspension type air heater [7Q] using quartz sand 0·5–0·75 mm dia. An equation [6Q] is presented which allows the prediction of heat transfer coefficients during scale formation.

Regenerator type heat exchangers found attention in several papers [4Q, 9Q, 12Q–14Q]. Included are matrices from glass ceramic surfaces, laminar flow matrices, and porous media.

The performance of heat pipes was studied experimentally by measurement of the liquid layer thickness through neutron radiograph [15Q], and new shapes leading to improved performance were described [8Q].

Aircraft and space vehicles

Ablation, heat shield performance, and other thermal protection systems for space missions are still of great interest in the field of aerospace applications. The behavior of a phenolic nylon ablator subjected to transient heat inputs reveals an intrinsic difference between increasing and decreasing heating [31R]. A new theory for the equilibrium shape of an ablating nose in laminar hypersonic flow produces results which agree well with the experimental shape near the nose, but deviate from the actual shape in the shoulder region [12R]. The effects of internal heat conduction and shape change on the calculation of the ablation of a metal axisymmetric nose tip are significant and should be considered in the treatment of an ablating, blunt-shaped object [29R]. Six thermal properties of a charring carbon phenolic material are measured simultaneously utilizing two hyperthermal plasma-arc facilities. The calculated property values derived from these tests are in good agreement with values from conventional tests [27R]. Other model tests also conducted in arc-heated gas streams reveal the effect of gas composition on the ablation performance of phenolic nylon [4R]. In a similar study, the interaction of gases with ablator and ablator components are investigated [3R]. The composition of the pyrolysis products from the decomposition zone of a charring ablator plays an important role for the heat transfer processes taking place in the char zone and in the boundary layer [28R]. An integral method is applied to solve the transient heat conduction problem involving an eroding surface exposed to erosive environments [30R].

The protection from solar flare radiation for astronauts on deep space missions is emphasized utilizing active or passive methods [11R]. For the thermal protection system of entry vehicles, the maximum permissible temperature at the bondline between the insulation and the backup structure has a strong influence on the choice of materials for insulation and backup structure [13R]. A study of the radiation interchange factors between adjacent layers of a multilayer insulation blanket shows that diffuse reflectance models allow a good approximation for blankets utilizing continuous diffusing spacers, such as tissue glass [22R]. Investigations of astronaut cooling systems for extravehicular space missions indicate that cooling in excess of evaporation of 2 or 3 per cent of body weight requires utilization of liquid cooling systems [16R]. Some large complex spacecrafts require an active environmental control system; a computerized thermal modeling of such control systems has been attempted [5R]. The development of the thermal protection system for Apollo spacecraft is chronologically discussed [8R].

Scale modeling problems are considered for thermal control coatings to control radiant heat transfer on the spacecraft [21R]. Surface control techniques allow thermal modeling of multilayered insulation for spacecraft thermal protection [10R]. In order to qualify the lunar module test vehicle (LTA-8) for an earth orbital mission, solar radiation is simulated by the use of conformal skin heaters controlled to predict heating rates [14R]. An analytical model is able to predict the effects of circumferential wall temperature gradients in spacecraft radiator tubes [39R]. The transient response of fin-tube space radiators is studied for a situation in which the steady-state operation is suddenly halted and the system is allowed to cool [25R]. The application of heat pipes for cooling of rocket nozzle throats is considered. For space operation, use of heat pipes for transfer and space radiators for rejection of the heat appears feasible [36R].

Various simulation and scaling techniques are discussed in conjunction with future space missions and for other applications. In connection with the Viking project, the effect of Mars dust erosion environment on thermal control coatings of the landing vehicles has been studied. The erosion of the hard materials increases as exposure time and dust density increases, whereas the more resilient coatings are not affected [1R]. Five model atmospheres are applied to simulate the Martian atmosphere in order to evaluate effective sky temperatures [38R]. A prediction of the temperature variation in shadowed lunar craters is attempted by utilizing simplified crater models [2R].

There are two possible heat sources for the sunlit ionosphere of Venus, namely photoionization of the neutral species (mainly CO_2) and influx from the solar wind [40R]. A study of the infrared transmission properties of CO, HCl and SO_2 leads to the conclusion that none of the above gases are significant for the strong greenhouse effect on Venus [7R].

The observed energy flux in the quiet solar wind is in good agreement with that predicted by coronal expansion models, including heat conduction [17R]. A survey and study of the use of solar energy for power conversion systems for orbital missions confirms the potential usefulness of heat storage systems utilizing the heat of fusion and the sensible heat of a material such as LiH [20R]. The reflection of solar simulator fluxes from CO_2 cryopanel deposits less than 100 μ thick has a negligible effect on the thermal balance of a test article in a space chamber [24R].

Simple scaling relations for heating of ballistic entry bodies are derived based on three parameters describing the body, the flight path, and the atmosphere [37R]. A method for the inclusion of fluid-flow phenomena in a heat transfer computer program is suggested which relieves the difficulties presently experienced with stringent stability criteria [41R].

Radiative heat transfer between a plane source simulating an aircraft runway and an aerosol (monodisperse natural fog) is investigated through the Monte Carlo method [34R]. The measured effect of radiant energy flux on the atmospheric pressure burning rate of a solid propellant demonstrates that this effect is negligible except when the propellant burning rate is very low [15R]. Normally neglected thermal gradients in solid propellants can have a significant effect on the results of stress analyses [33R]. Considering the cooling requirements for a turbojet powered Mach 3 transport using methane fuel, it is found that blade and wall cooling requirements increase rapidly with increasing turbine inlet temperature [9R].

The heat transfer predictions from four simple calculation methods are compared for a turbulent boundary layer on a flat plate in connection with lifting of entry vehicles [26R]. Turbulent boundary layer profile data are obtained from the smooth underface of an airplane fuselage for a Mach number range from 0·51 to 1·72, angles of attack up to 7 degrees, and Reynolds numbers up to $7{\cdot}4 \times 10^7$ [32R].

An analytical study of catalyzed hydrazine decomposition reaction chambers shows that radial variations in mass flow rate or bed packing cause radial temperature and concentration gradients that lead to turbulent diffusion of heat and mass in the reactor system [18R].

Air and helium transpiration cooling applied to a 7·5 degree cone at Mach 10 through a porous section near the apex shows that large decreases in the heating are obtained just downstream of the transpiration region even with small masses of coolant [6R].

Experimental results of an anode heat transfer study in an MPD arc confirm the validity of a simple anode energy transfer model [35R].

A first approximation heat transfer relationship is derived which allows to calculate the convective heat transfer as a function of the Reynolds number and the basic geometric parameters of a vortex combustion chamber [23R].

The results of heat transfer experiments and theory are reviewed pertinent to the processes which affect the calculations of high altitude balloon performance and the thermal design of their instrument packages [19R].

General

Heat transfer in gas turbines was studied as influenced by angle of attack [9S], by centrifugal forces [10S], by the turbulence level in the approaching stream [5S]. Increases in Nusselt number up to 40 per cent due to turbulence and unsteadiness of the flow were measured. The relation $Nu = a\,Re^{0.58}$ describes heat transfer to an exhaust valve according to model measurements [1S]. A considerable fraction of the heat transfer in ceramic oxide fuel elements for nuclear power plants is by radiation [13S]. A number of papers deal with cooling towers [3S] and [7S], with air washers [15S], with condensers [8S], and focus attention on thermal pollution [2S, 6S].

Plastic foam insulation for cryogenic applications [11S, 16S] shows an almost linear decrease of thermal conductivity with absolute temperature. Cooling methods for super conductivity magnets were described [12S]. Application of plastic foam can cut the energy required for electric snow melting in half [14S]. Effects of design variables on drill temperature were evaluated [4S].

PLASMA HEAT TRANSFER

Heat transfer studies in ionized gases reported during the past year refer to fundamental investigations as well as to applications. Heat fluxes play an important role in the low-frequency instability range of a collisional plasma requiring significant corrections to drift wave theories based on isothermal (or adiabatic) approximations [16T]. Analytical results of the electron heat transfer to a spherical body immersed into a weakly ionized, quiescent, non-equilibrium plasma are presented as a function of the body potential [8T]. A theory for the heat transfer to the stagnation point of a hemisphere in a supersonic, high-enthalpy, low-density nitrogen plasma flow is in agreement with pertinent experiments within 10 per cent [11T]. A new method based on the absorption of soft x-rays for determining densities in the boundary layer between a cold wall and a high temperature gas (up to 2500°C) or a plasma is described and measured temperatures and velocity distributions are presented [17T].

Spectrometric measurements in free-burning argon arcs seem to indicate that complete LTE requires electron densities of approximately $10^{18}\,cm^{-3}$ corresponding to pressures of approximately 3 atmospheres [2T]. The general wall parameter correlations such as apply for low and moderate temperature flows cannot be obtained for field-free plasma flows [7T]. Axial and radial temperature measurements in a supersonic ($M = 2.5$) weakly ionized plasma jet in argon indicate a lack of equilibrium among various energy modes [9T].

A simplified theoretical model shows that the mass injection rate determines whether or not a high current arc of the MPD type operates in a stable mode. The theoretical predictions are in reasonable agreement with experiments using argon and helium injection [4T]. Experiments with magnetically stabilized electric arcs in supersonic sulfur hexafluoride cross flow at Mach numbers up to 6.5 indicate that the arc slants across the electric field at angles such that the cross flow Mach number ranges from 0.8 to 3.8 [3T]. Forced convection has a profound effect on the shape and the associated isotherm distribution of an electric arc in cross flow [1T]. Time resolved spectrometric temperature measurements in moving arcs in argon are reported and the authors assume circular cross section of the arc [6T] which is questionable according to [1T].

A short review of the physics of alkali metal coated solid electrodes in contact with alkali seeded dense plasmas is reported. The results of the analysis suggest that ion densities could be very high near negatively biased boundaries [14T].

The validity of a simplified anode energy transfer model applicable to MPD arcs is demonstrated experimentally with a segmented anode. For the conditions studied in this paper, 70–80 per cent of the anode heat flux is carried by the electron current [15T]. A momentum parameter describing the relative strength of cathode to anode jet in a high intensity arc with a transpiration-cooled anode allows the prediction of the transition from a useful mode of operation to a burnout mode of the anode [5T].

A new method is proposed for a controlled generation of monodisperse ultrafine aerosols (< 100 Å) using a transpiration cooled graphite anode in a high intensity arc in argon at atmospheric pressure [12T].

A corona discharge originating on a heated wire is able to increase the otherwise natural convection heat flux by a factor of 4. This increase is probably due to a disruption of the boundary layer around the wire [13T].

The formation of N_2H_2 in a plasma jet is favored by low temperature levels, short and uniform residence times, utilization of liquid ammonia in abundance, and by the application of heavy gases in the plasma jet itself [10T].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Thermodynamic properties

Activity in the area of thermodynamic properties extends over a wide range of substances, properties, and conditions and includes experimental and theoretical investigations.

Mansoori and Canfield [56U] and Mansoori and Leland [57U] review perturbation and variational approaches to equilibrium thermodynamics of gases, liquids, and phase transition and give a variational approach to the equilibrium thermodynamic properties of simple fluid mixtures. For continuum thermodynamics with surfaces, Fisher and Leitman [31U] consider restrictions on constitutive equations. For polyatomic fluids, McCoy and Dahler [59U] examine the second-order constitutive relations. The Van der Waals representation is considered by Van Kampen [88U] who uses it to portray a one-dimensional gas, and by Eschenmoser [24U] who describes its renaissance in characterizing fluid behavior.

In the vicinity of the critical point, Blomberg and Stormark [9U] give their attention to the analytical restrictions on the behavior of thermodynamic quantities. Viswanath and Kuloor [91U] present a new correlation for predicting critical temperature.

For materials with memory, Day [20U] undertakes the interesting task of developing a theory for the thermodynamics of such substances. For mixtures with several temperatures, Bowen and Garcia [10U] consider their thermodynamics.

Considering liquids specifically, Ubbelohde [85U] discusses their structure and thermal properties; Rabinovich and Abovskii [71U] present the equation of state of a monatomic liquid at high densities, and Toxvaerd and Praestgaard [84U] develop an equation of state for a Lennard-Jones fluid. Continuing, Theeuwes and Bearman [83U] present the eighth part of a series on the equation of state of dense fluids, a comparison of the internal pressure from the Py theory and the Lennard-Jones (6–12) potential with experimental results.

Johari and Goldstein [47U] consider the problem of quite viscous liquids and their transition to glass, specifically the secondary relaxations in glasses made up of rigid molecules. For second-order fluids, Huilgol [45U] analyzes the nature of steady temperature fields. Verbeke and co-workers [92U] give the equation of state for fluid argon and also calculate the scaling exponents. Isothermal compressibility for liquid water at 1 atmosphere is reported by Kell [49U] and the thermodynamic properties of carbon tetrafluoride from 12K to the boiling point are given by Smith and Pace [76U].

A concern for mixture properties is apparent in the number of studies which take up this general problem. Brief and Joffe [13U] give the P-V-T properties of mixtures having hydrogen as a component (and pure hydrogen as well). Blancett, Hall and Canfield [8U] investigate the helium–argon system at modest temperatures (-50 to 50°C) but up to 700 atm. Continuing with the helium–nitrogen system. Hall and Canfield [39U] report isotherms at -190°C, -170°C and -160°C up to 700 atm. The planetary CO_2–N_2 atmosphere attracts the interest of Freeman and Oliver [30U] who give high temperature thermodynamic and transport properties. The thermodynamic functions of the ethane-carbon dioxide system are reported by Khazanova and Sominskaya [50U] and the gas-liquid equilibrium of the oxygen-carbon dioxide system by Fredenslund and Sather [29U]. Employing Rayleigh light scattering, Haynes *et al* [40U] determine the thermodynamic properties of acetone, dimethyl sulfoxide and their solutions.

A number of papers report the results of investigations into phase boundary behavior. Thus, Shinoda [74U] gives the vapor pressure of carbon monoxide in condensed phases; Liu and Lindsay [54U] report similar information for D_2O from 106 to 300°C; and Ewing *et al.* [25U] study saturation pressures of cesium at temperatures and pressures near the critical point. For multicomponent mixtures, Hudson and van Winkle [44U] describe vapor–liquid equilibria for systems of mixed positive and negative deviations; Dalager [19U] considers the specific problem of such equilibria for binary systems of water with methanol and with ethanol at extreme dilution of the alcohols. Binary freezing point diagrams for some methyl ketones and their complete solubilities in acetone, methanol, benzene and carbon tetrachloride are given by Bailey and co-workers [4U]. Surface tension is the subject of an investigation by Egelstaff and Widom [22U] who consider this liquid property near the triple point and by Shipp [75U] who reports values of this property for binary mixtures of several organic liquids at 25°C.

Several papers deal with the thermodynamic behavior of systems in which there is continuing interest. Presnall [70U] reports *P-V-T* measurements on hydrogen from 200°C to 600°C up to 1800 atm; Chernyshov and co-workers [18U] determine the *P-V-T* behavior of helium based on experiment; McClintock and Silvestri [58U] describe improved procedures for steam property calculation; and Bender [6U] gives an equation of state for dissociated air which has entropy, enthalpy and pressure as variables. Chapin [17U] estimates the equilibrium thermodynamic properties of water at temperatures 1000–6000°C and pressures 10–250000 bars. Both thermodynamic and transport properties of air and combustion products of natural gas and ASTM-A-1 fuel with air are reported by Poferl *et al.* [67U]. Numerical techniques are described by Hall and Canfield [38U] who describe a least-squares method for reducing Burnett data to compressibility factors and virial coefficients, and Fokin [27U] who tests for the internal consistency of tables and diagrams of thermodynamic properties of substances.

Heat capacity data and methods useful in aquiring such information result from the activities of a number of investigators. Zalivadnyi [95U] uses a dynamic method for evaluating this property for a medium; Popov [68U] employs a differential method; while Yurchak and Filippov [94U] use radial temperature waves. For composite materials, Rosen and Hashin [72U] report effective thermal expansion coefficients and specific heats. Bromley *et al.* [14U] study sea salt solutions to 200°C and determine heat capacities and enthalpies. Rounding out the activity in this area, Hadden [37U] gives heat capacities for hydrocarbons in the normal liquid range, Strömsöe *et al.* [80U] similar data for alcohol vapors at atmospheric pressures, Stull and co-workers [81U] the low temperature heat capacities of 15 inorganic compounds, and Buyco and Davis [16U] the specific heats for aluminum from zero to beyond the melting point and an equation for representation of the specific heat of solids.

Matters related to temperature, its definition and measurement, receive the attention of Benedict [7U], Muijlwijk and co-workers [62U] who discuss the practical temperature scale of 1968, and Finkel'shtein [26U] who considers the possibility of deriving a temperature scale by means of the absolute optical method. Miscellaneous studies include Lounasmas' discussion [55U] of new methods of approaching absolute zero, Boyes and Ponter measurement [11U] of contact angles encountered during distillation of binary liquids on a copper surface, and a review by Potter [69U] of the Joule–Thomson effect in superheated steam.

Transport properties

In the area of diffusion, Horne and Anderson [43U] consider pure thermal diffusion and a time-dependent phenomenological theory for binary liquids; Hidalgo *et al.* [42U] consider thermal diffusion and the Senftleben–Beenakker effect.

Thermal conductivity determinations continue to attract study across a broad front. Srivastava and Sharma [78U] consider transport coefficients of simple metals; Jain *et al.* [46U] continue their study of metals and report results for zirconium; Buckley [15U] considers conductivity and shock (thermal) qualities of zirconia coatings on thin gage N—Mo—C metal; and Ashley and colleagues [2U] report conductivity values for some 400-series stainless steels. Liquid metal thermal conductivity is determined by Neal [64U] using diagram techniques, and for frozen soils, Penner [65U] gives conductivity values.

Viswanath and Rao [90U] treat the thermal conductivity of liquids and its temperature dependence.

In the gas phase, there are a number of papers giving results for specific systems: Methane [79U]; hydrogen, nitrogen and argon electrical and thermal conductivity measured at high temperatures [61U]; steam [12U]; and for helium, a virial expansion form for medium density using various intermolecular interaction models [96U]. For multicomponent mixtures of non-polar gases, experimental results and prediction procedures are given [73U].

The variety of measurement schemes for determining thermal conductivity is apparent from the following articles: First, Vardi and Lemlich [86U] present a theoretical approach to a technique for measuring this property at high temperatures. The pulse method for determining thermal diffusivity of poor heat conductors is explored by Egorov and Kilesso [23U]. Bach and Grigull [3U] use optical recording with an unsteady-state approach. In a two-part study, Kumada and Kobayashi [51U, 52U] use a transient heating method for determining the diffusivity of a solid disk with thermal radiation from all surfaces; periodic and stepwise heating are used. The line source method [34U] is applied to measurements under vacuum conditions and Gobrecht *et al.* [33U] describe an impulse method for measuring the heat conductivity of small particles.

Ben-Amoz [5U] considers the effective thermal properties of two-phase solids; Katayama and Okada [48U] report on transient comparison methods of simultaneous measurement of thermal properties; and Leidenfrost [53U] describes and gives results from an instrument for measuring many properties.

Analytical and theoretical papers conclude the thermal conductivity activity. Grigull *et al.* [35U] consider some relations between thermodynamics and transport properties; Pietrass [66U] treats quantum corrections to fluid transport properties; Gerhardts and Hajdu [32U] work with the linear response theory of transport phenomena in dilute polyatomic gases; Grossmann [36U] presents some statistical calculations of transport properties; and Svehla [82U] calculates transport properties of complex mixtures. For heterogeneous systems, Dul'nev and Zarichnyak [21U] review the generalized conductivity coefficients. Valkering and van der Marel [87U] study the influence of heat conduction on paramagnetic dispersion and absorption curves.

Viscosity measurements dominate the activity centered on this property. Thus, Hellemans *et al.* [41U] report values for liquid nitrogen and liquid oxygen along isotherms as a function of pressure, and Vaughan and Safar [89U] measure viscosity by the subharmonic pressure threshold for a bubble in a viscous liquid. For gases, Aeschliman and Cambel [1U] measure atmospheric argon viscosity from 3500 to 8500°K; Vermesse [93U] measures the viscosity coefficient of nitrogen at high pressure. Water and steam viscosity at high temperatures and pressures is reported by Nagashima and Tanishita [63U]. For mixtures of the refrigerants R-12 and R-22, Srichand and co-workers [77U] give viscosities. Glass viscosity is measured at a 1000°C by Fontana [28U] using a parallel-plate viscometer. Misra and Parida [60U] calculate the coefficient of viscosity for some polar and ionic liquids using Misra's theoretical model.

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