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HEAT TRANSFER—A REVIEW OF 1971 LITERATURE

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INTRODUCTION

THIS review surveys research in the field of heat transfer, the results of which have been published during 1971. In general, it appears that the rapid progress in the 1960's has now slowed down and that a reassessment of past accomplishments and the establishment of goals for future research are of concern to the heat transfer community.* A trend toward applications, common to all engineering sciences, is becoming evident in the field of heat transfer. This is demonstrated by topics of the lectures presented at various meetings during 1971. It is less reflected in the papers published during that year. The number of these papers is still such that a selection only can be included in this review. A more detailed listing is contained in the *Heat Transfer Bibliographies* published periodically in this journal.

The 1971 International Heat Transfer Seminar held at Trogir, Yugoslavia on 6–11 September was devoted to the subject "Heat Transfer in Liquid Metals". Fifty papers, ten invited lectures, and two panel discussions were presented. These seminars are now organized yearly by the International Centre for Heat and Mass Transfer, which also publishes a *Newsletter* periodically. The Eleventh Conference on Thermal Conductivity, held at Albuquerque, New Mexico, 28 September–1 October, considered heat conductivity, primarily in liquids and gases.

On the national scene, a number of meetings were devoted exclusively or partly to heat transfer. The Twelfth National Heat Transfer Conference at Tulsa, Oklahoma, 15–18 August, presented twelve sessions on various topics, an invited lecture by W. M. Kays of Stanford University on "The Transpired Turbulent Boundary Layer," and another by J. R. Fair, Monsanto Company, on "Process Heat Transfer by Direct Face Contact, State-of-the-Art". The 92nd Winter Annual Meeting of the American Society of Mechanical Engineers, held 28 November–2 December at Washington, D.C. contained in its program twelve sessions which, among other subjects were devoted to: heat pipes, environmental and geophysical heat transfer, and biological systems. An Open Forum, in which brief reports on recent research results are presented, is already an established feature of this meeting as well as of the National Heat Transfer Conference. Preprints of the papers are available through the Society, and many of them will also be published in the *Journal of Heat Transfer*. The Annual Meeting of the American Institute of Chemical Engineers was conducted at the same time at San Francisco, California. The papers presented at this, and at other AIChE meetings, are contained in special issues of the *Chemical Engineering Progress Symposium Series*. Number 113 in Vol. 67 (1971) of this series has the title: "Convective and Inter-Facial Heat Transfer;" No. 119 is entitled: "Heat Transfer Aspects of Commercial Power Generation;" No. 116, entitled "Fluidization: Fundamental Studies, Solid–Fluid Reactions, and Applications," contains several papers on heat transfer. The 24th Annual Gaseous Electronics Conference and Third Arc Symposium held 5–8 October 1971, at Gainesville, Florida contained in its program papers on the thermal

* R. Sabersky, *Int. J. Heat Mass Transfer* 14, 1927 (1971).

state, the radiation, and the transport properties of plasmas and electrode phenomena.

An unusually large number of books relating to heat transfer, either new ones or new editions, has been published in 1971, especially by McGraw-Hill publishers. They are listed at the end of this paper.

Developments in heat-transfer research during 1971 can be characterized by the following highlights: The availability of large electronic computers facilitated finite difference solutions for a broad range of heat transfer problems including conduction with phase change or under transient conditions; laminar heat transfer in duct flows; boundary layers under non-uniform conditions; natural convection on vertical heated plates, in horizontal layers heated from below, and in enclosures of various shapes; and rotating flows. Finite rate chemistry was included in a boundary layer analysis with up to 16 reaction steps and up to 7 species involved.

Various analyses for turbulent heat transfer included models for turbulent diffusivity and turbulent Prandtl number, differential equations describing turbulent transport and, in particular, surface renewal models. The input required for these models was obtained by experiments on channel and boundary layer flow, on separated flow, in packed beds, and on rotating flows. Studies concerned with change of phase concentrated on bubble dynamics and on direct contact heat exchangers. Experimental results were obtained for radiative heat transfer in enclosures with a non-participating medium for the purpose of evaluating the accuracy of various analytical models. Research on radiative heat transfer in enclosures with a participating medium concentrated on the non-gray nature of radiation and on simultaneous conduction, convection, and radiation. The heat pipe found considerable attention. The Technology Application Center at the University of New Mexico offers a bibliography on this device which is issued quarterly. The ablation process in space shuttle vehicles and the formation of surface roughness by ablation was studied.

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

Current interest in conduction heat transfer appears to be primarily directed to problems involving phase change and various transient situations. In two-dimensional sublimation phase change problems, the accounting of lateral conduction gives rise to a smoother surface shape than is given by a locally one-dimensional treatment [53A]. The solution for transient heat conduction in a corner with melting or freezing was constructed by superposing two problems: first, a heat conduction problem without phase change and second, the problem of a distributed moving source of heat in a medium initially at zero temperature with boundaries maintained at zero [48A]. The interface velocity for one-dimensional melting or freezing in a body with variable cross-sectional area can be found from the interface velocity for a corresponding body of constant cross section [32A]. Equations and graphs are presented for the calculation of melting and solidification times for plane, spherical, and cylindrical bodies [54A]. An extensive tabulation of coefficients is given for evaluating the temperature distribution, heat flux, interface location, and interface velocity for freezing in a semi-infinite region [13A].

A regular perturbation expansion was used for the temperature field and interface location for ice formation in a long cylindrical tube cooled by external convection [36A]. A perturbation solution was also developed for the formation of an ice layer at the edge of a semi-infinite domain of water, initially at the freezing point and subject to a prescribed variation in surface temperature [35A]. By the use of a quasi-steady constant property model, a solution was obtained for the transient temperature distribution and the position of the sublimation front for freeze drying of slabs, cylinders, and spheres [20A]. A phase change problem involving a solid wall, a thin liquid film, and a vapor environment was investigated in connection with the microlayer evaporation model for nucleate pool boiling [25A]. A free boundary problem similar to melting or freezing, but with different boundary conditions, arises in connection with the theory of diffusion flames, diffusion of oxygen and lactic acid in tissue, and in the study of seepage when account is taken of molecularly bound water [49A].

In a numerical technique for the solution of the one-dimensional Stefan problem, the method of lines was employed to approximate the partial differential equations at discrete time levels [42A]. The use of Green's functions in melting and freezing problems facilitates an efficient finite-difference method of solution [12A]. Electrical circuits are described for simulating one-dimensional heat conduction and mass diffusion including phase changes [23A]. The most general existence and uniqueness theorem obtainable from the maximum principle for the Stefan problem has been derived [10A]. Continuity and differentiability properties of the solution of a melting–freezing problem have been investigated [52A].

Transient conduction without phase change was analyzed in numerous publications. Continuum equations governing the transient thermal behavior of a laminated composite can be deduced from the three-dimensional equations of heat conduction when a suitable weighting parameter is introduced [4A]. Synthesis methods are described for solving steady, three-dimensional composite media problems by the blending of known two-dimensional solutions [60A]. A composite-medium transient heat conduction problem including distributed and discrete heat sources was solved by using a substitution that leads to homogeneous external boundary conditions and then using a Vodicka type of orthogonality relationship [15A]. A memory theory of heat conduction was proposed which depends on the present value of the temperature gradient as well as on past values [45A].

The governing equations for transient heat conduction in bodies of small internal resistance were deduced by formal integration over the volume of the body [56A]. Optimized one-term solutions for transient heat conduction problems in one- or multi-dimensions showed surprisingly good agreement with exact solutions at relatively small times [27A]. Linearization of the radiation boundary condition for one-dimensional transient heat conduction problems was proposed along with an iterative scheme for finding the coefficients in the linearized representation [55A]. An extensive and valuable survey of methods of solving the non-linear equations of unsteady heat conduction has been published [38A].

The use of a lumped thermal resistance for a wall, *in lieu* of the complete heat conduction equation, was examined in connection with transients in heat exchangers [30A]. Collocation was used in conjunction with an assumed polynomial form of solution for the transient heat transfer in a slab, one face of which loses heat by thermal radiation [50A]. Transient and steady solutions were derived for a semi-infinite diathermanous solid in which there is a distributed internal heat source due to absorbed thermal radiation [6A]. The temperature distribution in an infinite medium resulting from a line heat source of finite duration was found by integrating the solution for an instantaneous source [43A]. Four layers—a dust layer, an anorthosite layer, a basalt layer, and a dunite layer—have been used to model the surface of the moon 4·1 billion years ago [34A]. The thermal history of the embedded basalt layer was determined to investigate whether the solidification of the basalt could have been delayed about one billion years, thereby explaining the observed age difference between the rock and the dust. Various perturbation series were employed for the analysis of the transient temperature field in a semi-infinite solid having temperature-dependent thermophysical properties [2A, 17A, 18A]; one of the series methods is reminiscent of the Görtler series for the fluid flow boundary layer [18A].

Comprehensive numerical results are given for the transient thermal response of a sphere and its heat conducting surrounding environment; the two regions have different thermophysical properties and initial temperature distributions [28A]. For this same problem, a less extensive presentation of results was made in [8A], where emphasis was placed on various initial temperature distributions. Temperature–time charts are presented for a two-layer composite cylinder subjected to a step change of temperature at its inner bounding surface [5A]. Transient temperature distributions are found for round and slab-type loads heated by electric induction [26A]. Such heating finds application for surface hardening of carbon steel or in the forging of heavy steel sections.

A variational formulation based on the method of local potential was developed and applied to the non-linear transient heat and mass transfer during drying of a moist body [31A]. The Kantorovitch variational method was used to solve for the transient temperature field in a hollow spherical shell [46A]. A variational formulation for transient heat conduction in polygonal plates can be transformed into a circular region, thereby facilitating its solution [61A].

The conventional energy conservation equation for transient heat conduction gives rise to an infinite propagation velocity for temperature waves caused by step changes at the body surface. Several recent papers have been concerned with alternative forms of the energy equation which yield finite propagation velocities. It was demonstrated that the finite propagation speed of temperature waves may have significant effects in determining the temperature rise of crystals caused by exothermic reactions [11A]. The finite wave speed for a one-dimensional transient was shown to depend on the instantaneous thermal conductivity and specific heat [1A]. The existence of a finite propagation velocity for thermal waves in solids was examined more rigorously than in the past [40A]. A variational method was devised which corresponds to transient heat conduction with finite wave speeds, that is, to the hyperbolic heat equation; to deal with the classical case of infinite wave speed, the relaxation time is set equal to zero [57A, 58A].

Various topics in steady-state heat conduction were studied in recently published papers. The accounting of temperature-dependent thermal conductivity in the one-dimensional treatment of a plane fin may lead to fin temperature distributions that differ appreciably from that for a fin of constant conductivity [29A]. Optimum fin profiles, corresponding to a minimum volume for a given heat transfer rate, have been found for fins which exchange heat by convection and radiation with the environment [14A]. Computations for an ensemble of rectangular fins which lose heat by convection and radiation (including mutual irradiation) indicate that the fin effectiveness decreases as the radiative contribution increases [19A].

In the presence of a temperature-dependent heat source, a steady temperature solution may not be stable against arbitrary perturbations [51A]. A number of examples confirmed that accurate steady-state temperature solutions for irregularly shaped bodies could be obtained by satisfying the boundary conditions in the least-squares sense [22A]. The use of bipolar coordinates facilitated the solution of a three-region heat conduction problem connected with nuclear reactor fuel elements [59A]. A quasi-steady model was employed to solve for the two-dimensional temperature field in a semi-infinite solid on whose exposed face there is a fast-moving arbitrary heat source; the solution is time-independent relative to a set of coordinates attached to the moving source [33A]. Methods have been described for solving steady heat conduction problems in walls which bound and interact thermally with adjacent convective flows [39A].

Numerical methods are frequently employed in the solution of practical heat conduction problems. The relative merits of finite-difference and finite-element methods have been examined and evaluated. For steady-state situations, it was found that the finite-element models are competitive with the finite-difference method in execution time, inferior in core storage requirements, and may be superior in accuracy. For transient problems or for variable-property steady problems, finite-difference methods are faster in execution and require less computer core storage [21A]. Systematic procedures are presented for reducing the order of a matrix differential equation evolved by the finite-element analysis of transient heat conduction in solids [24A]. A new explicit difference method for simultaneous quasi-linear differential equations is purported to possess both simplicity and stability [7A]. By using extrapolation techniques as an overlay on the primary algorithm, distinctions between the explicit and implicit methods become of lesser consequence [9A]. For finite-difference solutions of steady heat conduction problems, the rate of convergence may be accelerated by using an over-relaxation factor, the determination of which is discussed in [16A]. A variational method for solving numerically the transient heat conduction in a slab is compared with a classical difference scheme, the comparison being made for a case in which the conductivity is a linear function of temperature [37A].

Additional information has been published on thermal contact resistance. Analysis showed that thermal distortion could be responsible for the dependence of the thermal contact resistance between dissimilar materials on the direction of heat flow [3A]. Calculations have demonstrated that large errors in the prediction of the thermal contact resistance can result if solutions for bodies of infinite extent are employed for finite regions of interest [41A]. An analytical relationship was found between the thermal contact resistance and an external load applied to the surfaces of projections in the region of elastic and elastic-plastic contacts [44A]. Equations have been obtained from which the thermal contact resistance can be evaluated for initial and subsequent load applications [47A].

CHANNEL FLOW

For heat transfer in turbulent pipe and duct flows, there has been considerable interest in heat transfer augmentation, non-circular geometries, and prediction methods. Ducts with alternating diverging and converging sections, tested with turbulent airflow, were shown to transfer more heat than constant area ducts for the same pumping power and surface area [29B]. The influence of repeated-rib roughness on turbulent flow in tubes was studied for air and liquids in the Prandtl number range from 0·71 to 37·6. The friction data were correlated using the law-of-the-wall similarity, whereas the heat–momentum analogy led to a successful correlation of the heat transfer data [75B]. Tests conducted with subcooled water at 50 atm flowing turbulently in an electrically heated tube containing a twisted tape gave a linear dependence of the Nusselt number on the Reynolds number [10B]. Whereas most studies of heat transfer in the presence of turbulence promoters use inserts along the entire tube length, experiments have been performed in which the swirl generator is situated only in the initial part of the tube [42B]. Heat transfer and pressure drop data for parallel-plate channels with corrugated walls of various types were correlated so as to facilitate heat exchanger design [7B]. Electrochemical mass transfer measurements in the separated and redeveloping regions downstream of a sudden enlargement in a tube showed that the transfer coefficients reach a maximum about five step-heights downstream of the enlargement section [51B]. For small radii of curvature of the inlet section of a circular tube, there is a downstream separated region in which relatively high values of the heat transfer coefficient are attained [16B].

In a rod bundle in which there is longitudinal turbulent flow and $Pr \sim 1$, the distinction between circumferentially uniform rod surface temperature and circumferentially uniform rod heat flux vanishes when the pitch-to-diameter ratio is greater than 1·25 [32B]. Nusselt number results for various pitch-to-diameter ratios were brought together on a nearly universal line [9B]. Sublimation of naphthalene, camphor, paradichlorobenzene, and thymol in air was employed to measure laminar and turbulent mass transfer for longitudinal flow through a rod bundle [47B]. An analysis of simultaneously developing turbulent velocity and temperature fields in an annulus with a heated inner core indicated that hydrodynamic development is completed within 10 equivalent diameters, but that an additional 30 equivalent diameters are required for the thermal boundary layers to reach the outer insulated wall of the annulus [76B]. Erosion rates of subliming naphthalene were used to determine local mass transfer rates at the inner bounding wall of a concentric annulus for airflow Reynolds numbers ranging from 2100 to 55000 [35B]. Entrance region and fully developed turbulent heat transfer coefficients were measured for subcooled liquid nitrogen flowing in a heated annulus [3B].

The circumferentially averaged Nusselt numbers for a narrow triangular duct were about 50 per cent lower than those for a circular tube and agreed quite well with the experimental results of Eckert and Irvine [31B]. A newly proposed characteristic length for correlating turbulent Nusselt numbers in non-circular ducts takes account of the largest and smallest curvatures of the isovels [1B]. A method for treating turbulent flow and heat transfer in ducts of arbitrary cross section matches the velocity distributions in the core and wall regions along an isovel [4B].

Surface renewal models are based on the notion that eddies intermittently move from the turbulent core to the close vicinity of the wall, where simple one-dimensional unsteady molecular transport is assumed to predominate. A model which accounts for the effect of eddies not moving into direct contact with the wall yielded good temperature profile predictions for turbulent pipe flows [68B]. A wall turbulence model relating surface renewal frequencies to energy dissipation in the constant stress layer was successfully employed to predict turbulent Sherwood numbers for tube flow at high Schmidt numbers [5B]. Ruckenstein's surface renewal model for predicting the temperature field in turbulent tube flows is based on the concept that turbulent transfer may be characterized by a mosaic of laminar, quasi-steady, boundary layer type processes. The validity of the quasi-steady surface renewal model was questioned due to (1) its failure to predict temperature profiles for values of Pr greater than 5·7 and (2) its failure to correlate data for the mean Nusselt number for values of Pr between 0·5 and 5·0 [67B]. Successful application of surface renewal models for turbulent flow in rough tubes still awaits additional information regarding the mean frequency of renewal [66B].

A continuous cross sectional distribution of the eddy diffusivity was used to predict fully developed turbulent Stanton numbers for pipe flows at high Prandtl numbers [59B]. Another analysis for high Schmidt (or Prandtl) number mass (or heat) transfer in turbulent tube flow led to a $\frac{1}{3}$-power dependence of the transfer coefficients on *Sc* or *Pr* [38B]. Matched asymptotic expansions were employed to find analytical expressions valid for the intermediate and larger eigenvalues for the turbulent Graetz problem with uniform heat flow. Numerical results are presented for the liquid metal range of *Pr* [43B]. A new analogical relation between heat and momentum transfer in turbulent pipe flows contains two new dimensionless groups and was deduced by employing ideas from Prandtl and Schlichting [60B]. Eddy diffusivity information for turbulent pipe flows was reviewed and a model for heat and mass transfer was proposed for the range of Prandtl and Schmidt numbers from 0·02 to 100000 [25B]. Various models for the laminar sublayer of turbulent pipe flow were considered and compared with experimental observations, with special emphasis on predictions of heat and mass transfer [24B].

Measurements utilizing continuous injection of a tracer gas into an airflow indicated that the eddy diffusivity for mass varied linearly with the Reynolds number in the central region of a tube [56B]. According to [63B], turbulent forced convection heat transfer to a supercritical fluid in tube flow is not a new type of heat-transfer problem, but can be predicted by a conventional variable property analysis. The end states for the freezing of a turbulently flowing liquid in a pipe have been calculated for the conditions of constant mass flow rate of the liquid and of given constant pressure drop along the tube length [19B].

Secondary flows are encountered in a variety of duct flow situations. Finite difference calculations for the temperature field in a turbulent flow in a square duct demonstrated the presence of a secondary flow [26B]. Experiments and analysis for laminar flow in a uniformly heated curved duct of square cross section indicated that the flow and temperature fields are strongly influenced by the secondary flow which is caused by the curvature [40B]. In the laminar thermal entrance region of a helical tube, the effect of secondary flow on the heat transfer was found to be small, owing to the thin thermal boundary layers [15B]. Heat transfer and friction factor results for laminar flow in curved pipes were obtained numerically by a combination of the line iteration method and the boundary vorticity method; the separate dependence of the Nusselt number on the Prandtl number was eliminated by introducing a new dimensionless grouping [2B]. In a straight pipe rotating about an axis perpendicular to that of the pipe, there is a secondary flow caused by the Coriolis force. The effect of the secondary flow is to increase both the friction factor and the Nusselt number [39B]. Experiments involving laminar flow of oils in vertical, heated rectangular ducts demonstrated the existence of superposed natural convection effects, which depended on the magnitude of a modified Rayleigh number [41B].

Investigations of heat transfer to laminar pipe and duct flows are, for the most part, analytical. Graetz-type solutions obtained for laminar tube flows with other than parabolic velocity profiles indicated that the Nusselt number increases when higher velocities exist near the tube wall [6B]. The use of Green's functions in generalizing solutions of the Graetz problem to more general boundary conditions was described [20B]. Radiation heat loss from the outside surface of a laminar tube flow gives rise to local Nusselt numbers that fall between those of uniform wall temperature and uniform heat flux [28B]. The use of the finite-element method was illustrated by application to the developing laminar temperature field in the thermal entrance region of a parallel-plate channel [65B]. The proper boundary conditions for initiating a numerical solution for developing laminar flow and heat transfer in a circular tube were examined [72B].

For laminar flow in porous-walled tubes, mass injection increases the thermal development length and extraction reduces the thermal development length [45B]. The heat transfer results for laminar flow in tubes and channels with wall injection and suction showed a nearly universal dependence on a Peclet number based on the wall velocity [49B]. Finite-difference solutions were carried out for the laminar thermal entrance region for uniform injection or suction at the walls of a parallel-plate channel [14B].

A finite-difference technique was used to investigate the effect of axial conduction on the local and mean Nusselt numbers for the Graetz problem in tubes and channels, but heat conduction across the entrance cross section was neglected [54B]. Solutions investigating the axial conduction effect in laminar tube flow indicated that conduction upstream of the entrance cross section should not be neglected; that is, the temperature distribution across the entrance section is not uniform [27B]. Axial conduction effects in low Peclet number laminar tube flow were analyzed by separately solving the energy equations for the regions upstream and downstream of the thermal inlet section and then matching the results [23B].

Analysis showed that for laminar creeping flow between parallel circular disks with an eccentric inlet, the heat transfer was decreased if the eccentricity was increased [64B]. Several fundamental solutions for thermally developed laminar heat transfer in eccentric annuli were obtained by employing the method of orthonormal functions, which satisfies the given boundary conditions in the least squares sense [71B]. The timewise development of the temperature field in plane Couette flow was analyzed in order to determine the time period during which viscous dissipation does not significantly affect viscosity measurements in a Couette flow system [77B]. The Wiener–Hopf technique was employed, in the limit of zero Prandtl number, to find an exact solution for the temperature field about a finite plate situated in a parallel-plate channel [30B]. The effect of flow pulsations on laminar heat transfer in a parallel-plate channel was found to depend on whether the pulsation frequency is low, intermediate, or high [13B].

Finite-difference solutions for laminar tube flow of air indicated increases in Nusselt number with heating and decreases in Nusselt number with cooling; wall friction was affected to a greater extent than was the Nusselt number [53B]. Air transport properties, represented by power-law temperature dependences, were employed in finite-difference calculations for laminar flow in heated annuli with either uniform or developed velocity profiles at the inlet [58B]. Numerical solutions yielded variable property results for the Nusselt number and pressure drop for simultaneously developing velocity and temperature fields in a channel with air flows at large temperature differences [11B]. Finite-difference techniques were also used to obtain variable property results for air and helium, but with a developed velocity distribution at the inlet cross section of the channel [62B]. Numerical finite-difference solutions and supporting experiments on laminar compressible gas flow in a uniformly heated tube gave local bulk Nusselt numbers that were very little different from those for constant properties [48B]. A simplified criterion was proposed for estimating the conditions under which viscous heating may be neglected in a Newtonian, laminar tube flow [18B]. A linear stability analysis for liquid flow in a parallel-plate channel showed that temperature-dependent viscosity is destabilizing, but that this result depended on the accounting of viscosity gradient terms in a modified Orr–Sommerfeld equation [46B].

Several papers have dealt with non-Newtonian flows. Solutions of the Graetz problem for a heat dissipating, non-Newtonian fluid indicated an increase in the fully developed Nusselt number due to the non-Newtonian behavior [57B]. For laminar flow of non-Newtonian fluids in a circular tube, it was found that the Nusselt numbers for pseudoplastic fluids are somewhat higher than that for a Newtonian fluid, whereas the Nusselt numbers for dilatent fluids are somewhat lower than that for a Newtonian fluid [34B]. Finite-difference solutions showed that for laminar flow in a circular tube, the mean Nusselt number for a Bingham plastic was higher than that for Newtonian fluid [52B]. Experiments indicated that laminar non-Newtonian heat transfer coefficients in flattened tubes are higher than those in circular tubes [44B]. Finite-difference methods enabled the examination of the effects of external resistance, non-Newtonian flow, and temperature-dependent viscosity on the Nusselt number for laminar tube flow with simultaneously developing velocity and temperature fields [37B]. A Taylor–Prandtl analogy was applied to predict turbulent heat, mass, and momentum transfer for non-Newtonian tube flow; a power law model was assumed in the laminar sublayer, but no commitment was made to a specific rheological model in the turbulent core [21B]. A new correlation for turbulent heat and mass transfer to power-law fluids at high Prandtl or Schmidt numbers was based on a continuous distribution of the eddy diffusivity across the section of the pipe and contained no adjustable constants [33B].

Solutions and results for mass transfer problems with and without chemical reactions can frequently be carried over to analogous heat transfer problems. For mass transfer in a turbulent pipe flow in the presence of homogeneous chemical reactions, the Stanton number increases with an increase in the dimensionless rate constant [50B]. The occurrence of two consecutive first-order chemical reactions in fully developed laminar or turbulent channel flows gives rise to sharp discontinuities in the local Nusselt number [36B]. For a porous-wall circular tube reactor under well-mixed plug flow conditions, the performance of the reactor is improved when the wall completely rejects reactant in the case of suction and completely rejects inert and product in the case of injection [55B]. Chemical conversion due to an irreversible first-order chemical reaction in laminar tube flow may be significantly influenced by non-Newtonian characteristics [22B]. Second-order chemical reactions, either at the wall or in the flowing fluid, were included in an analysis of laminar mass transfer in a tube and in a parallel-plate channel [8B]. A finite-difference method has been developed for turbulent pipe flow of non-reacting gases or of reacting gases, with surface mass transfer; in this connection, the van Driest formulation for the eddy viscosity was extended to include the effects of variable properties and surface mass transfer [78B]. The decay of the concentration field far from the entrance of a laminar-flow circular tube reactor was studied in the presence of first-order homogeneous and heterogeneous reactions [73B]. For mass transfer from the inner surface of a tube to a fluid in fully developed turbulent flow, the interfacial velocity has a pronounced effect on the mass transfer coefficient [74B]. The problem of laminar mass transfer in a flat duct with permeable walls is fully analogous to the problem of heat transfer in a duct with external thermal resistance at the walls; the numerical results, obtained from an analysis of the Graetz type, are interchangeable [12B].

Magnetohydrodynamic flows continue to be investigated. Finite-difference solutions for magnetohydrodynamic channel flow showed that temperature-dependent viscosity and electrical conductivity can cause large changes in the friction factor and volumetric flow, even for small property variations [69B]. Increasing intensity of the magnetic field strength brings about an increase of the fully developed Nusselt number in laminar MHD tube flow [61B]. Numerical solutions for laminar MHD channel flows with temperature-dependent viscosity, electrical conductivity, and thermal conductivity took account of property variations appropriate to liquid metals, electrolytes, and ionized gases [17B]. The magnitude and character of the limiting Nusselt numbers in MHD generators are very different from those for either MHD accelerators or electrically insulated ducts [70B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Laminar flow

A survey [24C] of recent research by H. Schlichting presents many research results including, in laminar boundary layers, the effects of wall temperature variation, fluid injection, three-dimensional flow, and mixed forced and free convection and, in turbulent boundary layers, the effect of upstream turbulence and three-dimensional flow.

The concept of local similarity was extended [26C] by including the effects of local distribution of injection at the wall and of freestream variation leading to non-similar conditions. The effect of non-uniform wall temperature was considered by treating a step discontinuity of temperature as a series of similar tabulated solutions [3C] or using integral conditions [25C]. The method of Cohen and Reshotko was extended [1C] to laminar boundary layers with large wall heating and flow acceleration. The temperature recovery factor decreases for accelerated boundary layers with an increase of the acceleration parameter β according to an analysis [34C]. For a gas with $Pr = 0{\cdot}715$, it has the value of 0·82 at $\beta = 0$ and decreases to 0·76 at $\beta = 20$. The effect of longitudinal surface curvature on heat transfer was analyzed by a perturbation on wedge flow solutions [7C, 12C]. Heat transfer parameters for three dimensional stagnation point flow of equilibrium air were calculated [33C] for spheres, cylinders, and saddle shapes and speeds up to 10 km/s, using the method of Fay and Riddell, and are listed in tables. The two-component boundary layer in hypersonic stagnation flow with temperature dependent properties created by teflon gas injected into air was analyzed [27C] using iteration of the integral form of the boundary layer equations. An analysis [18C] of the stagnation point boundary layer with hydrogen injection into air considered finite rate chemistry with 16 reaction steps and 7 chemical species. Numerical methods for chemically reacting laminar flows were compared [17C]. Approximate solutions of the dynamic and thermal boundary layers were obtained [5C] by linearization for non-Newtonian fluids obeying power-law relations.

Turbulent flow

Measurements [36C] of local heat transfer on a plate established the effect on transition of a turbulence promoter in the shape of a rectangular bar. A method by Van Driest (*Aero. Engng Rev.* **15**, 26, 1956) is recommended [9C] for the prediction of skin friction and heat transfer on flat plates at supersonic and hypersonic Mach numbers on the basis of comparisons with experiments. A correlation by Owens and Thomson (*J. Fluid Mech.* **15**, 321, 1963) describing heat transfer on rough surfaces was extended to supersonic flows [20C] and compared with experimental results at Mach numbers from 3 to 4·9. Reynolds analogy was found to be invalid for rough surfaces. Roughness was found [23C] to increase heat transfer and to accelerate transition in the supersonic region of a conical nozzle. Experiments [6C] established that heat transfer to slender bodies at a Mach number 5·2 is well predicted by a modified reference enthalpy method for laminar and turbulent flow. Measurements [19C] of temperature distributions in supersonic boundary layers at Mach numbers between 1·75 and 4·5 established that the turbulent Prandtl number has values around 1 or somewhat larger for $y^+ < 5$ and drops to 0·8 at $y^+ \sim 1000$. Use of a special Reynolds number results in standard values of the friction factor and Stanton number from relations obtained by the theory of vanishing viscosity [16C]. The surface renewal and penetration model applied [28C] to incompressible boundary layer flow resulted in the relation

$$Nu_x = 0{\cdot}296\, Re_x^{0{\cdot}8}\, Pr^{0{\cdot}5}$$

which compares well with experimental results for gases. Turbulent heat transfer measurements [31C] on a blunt cone at angle of attack and $Ma = 10{\cdot}6$ produced heat transfer coefficients which compared well with an analysis based on the stream line pattern obtained from experimental pressure distributions as long as the boundary layer was thin.

Unsteady flow

The temperature and heat transfer history of a solid sphere with high conductivity in unsteady forced convection flow at low Reynolds number was studied [4C, 14C]. Time mean friction factors and surface temperatures of an insulated flat plate in a fluctuating stream were found [11C] to increase with frequency and to be ultimately proportional to the square root of the frequency. Heat transfer for the same situation increases strongly with frequency mainly because of viscous dissipation [10C]. Acceleration of the flow also increases heat transfer and skin friction on a porous flat plate according to [35C] with the effect being stronger for blowing. Simple solutions are obtained [2C] with the integral method for transient convective heat transfer in fluids with vanishing Prandtl number. Capillary waves can decrease the mean temperature gradients in thermal boundary layers of water by a factor up to 9 whereas irrotational waves cause a decrease only up to a factor 1·381 [32C].

Miscellaneous

Heat transfer through a flat plate between two laminar boundary layers on opposite sides of the plate depends on the wall temperature variation created by the transfer process [29C]. This interaction can change the heat flux by up to 30 per cent for two cocurrent laminar boundary layers. Binary mist flow (water–air) in a laminar boundary layer was analyzed [8C] with the result that the mist causes a large increase in the wall heat flux whereas the increase in wall shear is negligible. Velocity and temperature profiles in compressible turbulent wall jets were calculated numerically [30C] using an expression for the turbulent diffusivity varying with wall distance and Reynolds analogy. Experimental results [22C] are reported for a heated jet ejected from a round hole into a turbulent boundary layer on an adiabatic flat plate under angles of 90 and 35°. Temperature, velocity, and turbulence intensity profiles are reported for blowing rates up to 2. The results may be applied to film cooling processes. The two-dimensional velocity field in a heated free jet at low Reynolds number (polymer or glass) was calculated [15C] and compared with experiments. Disagreement is probably caused by neglect of the temperature variation in the jet. The addition of valeric acid as surface active agent to a falling water film on a vertical heated tube has been shown [21C] to increase heat transfer at small concentration and to reduce it again at larger concentrations. The electron conservation equations were solved [13C] in the quasi-neutral region of re-entry boundary layers with the boundary condition of a collisionless sheath resulting in significant temperature non-equilibrium at a velocity of order 10 km/s and an altitude of 50 km.

FLOW WITH SEPARATED REGIONS

Single bodies

Cavity resonance (self-induced pressure oscillations) do not cause large changes in cavity heat transfer, and cavity thermal resistance characteristics are satisfactorily predicted by non-resonant theory [8D]. Laminar separation behind a rearward-facing step is solved numerically for the limiting case of infinite Reynolds number. The interaction between the inviscid eddy and the recirculating shear layer is treated [7D]. Masilyah [19D] discusses heat transfer mechanisms in the wake of an oblate spheroid at an intermediate Reynolds number of 100. Hurd and Peters [15D] analyze flow separation in a constant width channel with a sharp, 90° turn. Laminar separation bubbles occur at Reynolds numbers between 50 and 200. Hodson [14D] analyzes Hunt and Howell's experimental finding that adding an open honeycomb structure to a surface significantly decreases the temperature of that surface in hypersonic flow provided the cell depth is more than twice the cell width. Morozov [21D] investigates similarity of supersonic flows past rectangular recesses in plane and axially symmetric bodies. An integral analysis of slot cooling [17D] shows that coolant injection reduces total heating downstream of the slot, whereas local heating in the jet mixing and recompression regions may increase. Conditions which produce a subsonic flow that is laminar at both separation and reattachment do exist for a rearward-facing step [9D].

Experimental results [22D] are presented for the separated flow regions within altitude compensating planar and axisymmetric plug nozzles and expansion–deflection nozzles. The lip shock was not of significant strength to warrant inclusion in an analytical explanation, yet the sonic line was noticeably distorted. The effects of position, size, and number of holes on heat transfer to a circular cylinder with uniform surface heat flux and cooled by air passing through a ring of holes are obtained to determine optimum location of holes for minimum peak temperature [27D]. Thackston and Schnelle [26D] suggest a dead zone model to explain the sharp peak and longer tail observed in the dispersion of tracers in natural streams. Tracer material is noted to hang up in pockets and is then slowly released back into the stream.

Packed and fluidized beds

Fully separated subsonic flows occur in the flow of fluids over bluff shapes such as heat exchanger fins and surfaces. These separated flows are characterized by steady, sometimes periodic flow. An analysis based on the mechanisms of vortex shedding and boundary layer behavior is presented which compares well with experiments for two geometries that are representative of heat exchange surfaces [20D]. A method of finding three unknown parameters—heat transfer coefficient, thermal conductivity of packing, and longitudinal Péclét numbers—for a dispersion model of a packed bed of spheres with fluid flowing through it is described [11D], demonstrated by simulation [11D] and experimented [12D]. The literature of fixed beds, as reviewed recently by Barker, is enormous. It is shown in [1D] and in [24D] that the particles may normally be considered as perfect heat conductors while axial heat contion through the bed may be ignored. Heat loss through the sidewalls and the wall heat capacity should always be taken into account. Beveridge and Haughey [6D] study axial heat transfer in packed stagnant beds in order to isolate the mechanisms of conduction and radiation from convective effects. A relationship is given [25D] for the effective thermal conductivity of beds of unconsolidated particles from an analysis of the statistical nature of the heat flux lines and compared with 27 different experimental cases. Three papers on the modeling of chemical reactors describe a relaxation procedure for solving the nonlinear elliptic equations governing heat and mass transfer inside a catalyst [13D].

Beavers and Sparrow [5D] analyze compressible gas flows through porous media at velocities which are sufficiently high to cause significant inertia effects. A similar method is used to obtain results for a porous wall with a step in thickness, a wall with gas supplied through periodic slots in one boundary, and an eccentric porous annular region [10D]. Batchelor [4D] analyzes the stress system in a suspension of force-free particles. Allowance is made for three effects not usually considered: effect of body couples on particles, effect of inertia forces associated with velocity fluctuations above average, and the effect of surface tension.

In fluidized beds, a suspension of particles contact the packing surface, absorb heat, and return to the bulk of the suspension releasing heat. Heat transfer takes place rapidly at the packing due to vigorous contact and to the suspension because of high turbulence [23D]. Kalegin and Donat [16D] studied the effect of the depth of a fluidized bed on the solid-particle concentration distribution in the space above the bed.

The gas phase velocity at a plate submerged in a fluidized bed is higher than at the bed core.

Convection of the gas has a marked effect on the heat transfer from the surface to the fluidized bed [18D]. The angle of inclination of a thin plate (maximum heat transferred in vertical direction) was studied. Larger plates decreased heat transfer [2D]. The radiant heat transfer from a boiling bed to a surface submerged in it is still an unsolved problem [3D]. The effective thermal diffusivity in a liquid-fluidized bed test apparatus fit a semi-empirical correlation

$$k_{\text{eff}} = 5320 \frac{\rho_s C_{ps}}{\rho_f C_{pf}} \frac{Re^{0.25}}{Pr^{0.75}}$$

where Re is the Reynolds number based on the particle diameter and the root-mean-square fluctuation velocity [28D].

TRANSFER MECHANISMS

Shear stress, eddy viscosity, and mixing length distributions were obtained [3E, 4E] in a hypersonic turbulent boundary layer from velocity profiles assuming local similarity. An eddy viscosity model was proposed [7E] which produces the local distribution of velocity, shear, and turbulent energy production and dissipation in good agreement with experimental results obtained by Laufer. An eddy diffusivity expression [11E] in a turbulent boundary layer for $y+ < 45$ and for Prandtl numbers larger than 100 leads to the following formula for the developed Nusselt number Nu_∞

$$Nu_\infty = 0.0149\, Re^{0.88}\, Pr^{\frac{1}{3}}$$

resulting in agreement within 4 per cent with good experimental results. The mixing length theory of turbulent heat and mass transfer was improved [6E] by the postulate that the Reynolds stress is proportional to the square of the second derivative of the velocity in regions where this second derivative is large compared to the first one. Prandtl's mixing length equation is maintained otherwise. Applied to duct flow with heat transfer from the hot to the cold wall, these relations lead to temperature profiles which compare well with experimental ones. The results of experiments have been reported [2E] which measure the various terms in the turbulent energy balance equation. Newly proposed semi-empirical formulas [1E] for the eddy viscosity and the turbulence scale have the advantage that, when introduced into the continuity, momentum, and turbulent energy equations, they result in good agreement with experiments using almost the same constants for circular and plane jets and shear layers. The stability of fully developed turbulent flow along a wall for small disturbances was investigated [8E] using the time-averaged flow equations. The resulting equation could be reduced to the Orr–Sommerfeld equation by introduction of the stream function. It was demonstrated that turbulent flow can be stable against small disturbances. An analysis based on Lagrangian similarity [12E] studied diffusion from a line source into a turbulent boundary layer. Good agreement with experiments was obtained for a smooth wall and the influence of surface roughness and of polymer additives was studied using statistical turbulence theory. It was demonstrated [5E] that a shear flow with weak homogeneous turbulence is destabilised by buoyancy forces acting in the direction of the velocity gradient so that turbulence sometimes grows in downstream direction. The recently discovered wavy turbulence in a liquid–liquid (solvent–water) was investigated [10E] by flow visualization and the concentration profiles were measured by micro-interferometry. The 1970 von Kármán lecture [9E] presents an excellent review of our present understanding of the physics of turbulent flows with new contributions by the author.

NATURAL CONVECTION

Studies of natural convection kept pace with the general expansion in the number of papers related to heat transfer that have appeared in the past year. Interest remains strong in boundary layer flows and in flow and heat transfer in enclosed fluid layers. Areas of particular emphasis appear to be stability problems and basic heat transport mechanisms as opposed to applications to particular systems.

One geometry of continued interest remains the heated vertical flat plate. An asymptotic expansion was used [38F] to study free convection from such a geometry with a discontinuous wall temperature. The limiting case of very large Schmidt or Prandtl number was solved to give the heat or mass transfer from a vertical plate with uniform flux boundary conditions [57F]. Another analysis of laminar free convection at large Prandtl number used an expansion with inner and outer layers in the flow [16F]. Measurements have been made [54F] of the heat transfer and average wall friction for uniform surface heat flux to water. Calculations [44F] of the limiting time for pure conductive heat transfer with unsteady free convection agree well with earlier analyses. A boundary layer analysis for free convection on a vertical plate apparently can be used down to Rayleigh numbers as low as approximately 10 [27F]. An analysis was made [45F] of the flow of an electrically-conducting fluid in the presence of a magnetic field perpendicular to the gravitational force. Similarity solutions have been obtained [19F] for combined thermal and concentration natural convection boundary layers.

Transition to turbulent flow along a heated vertical plate has been studied considering two-dimensional disturbances [11F]. The stability of natural convection boundary layers of large Prandtl-number fluids has been examined [30F]. Measurements have been made of the instability induced in a natural convection boundary layer by a constant electric field [70F].

Measurements have been made of the velocity and temperature distributions in a vertical corner formed by two heated plates at right angles to each other [71F]. The peak velocity in such a flow is higher than that which would be obtained from a single vertical plate. Measurements have been made of the natural convection heat transfer from a vertical cylinder in the presence of an evaporating liquid [39F]. A three-dimensional boundary layer analysis has been made which holds asymptotically for low Prandtl-number fluids [63F].

An analysis extends results of previous theoretical studies on the free convection from a line source of heat at different Prandtl numbers [62F]. Measurements [25F] of convective heat transfer from a horizontal cylinder to carbon dioxide near the thermodynamic critical point show no discontinuities in the heat flux versus temperature difference curve; no "boiling-like" mechanism appears to affect the heat transfer in that range. Measurements of natural convection heat transfer from an oscillating horizontal wire were well correlated using the average wire velocity [3F].

Laminar plumes are found to be less stable for asymmetric than for symmetric disturbances [50F]. An experimental study of a laminar vertical jet in a stably stratified environment showed that the jet induced a torroidal cellular flow around itself [68F]. The shape of a plume trajectory from a hot chimney turns out to be strongly dependent on the atmospheric turbulence level [60F].

A numerical solution has been obtained for natural convection in horizontal cylindrical annuli. A transition to unsteady flow is indicated by this analysis [52F]. Calculations indicate [53F] that the natural convection in a horizontal cylinder whose wall temperature increases linearly with time only slightly augments the heat transfer which would be obtained for pure conduction.

Various studies on natural convection heat transfer from a horizontal surface have considered the effects of gas flow at the surface, temperature fluctuations, and stability. Interferometric measurements [6F] indicate the effects of suction and blowing at porous surfaces facing either upwards or downwards. A numerical study for a heated horizontal surface with mass infusion of a foreign gas from the surface indicates the heat transfer with such a flow [37F]. An analysis indicates the effect of time varying fluctuations on the temperature of a semi-infinite horizontal heated plate [59F]. Measurements have been made [49F] of the combined effects of surface tension and buoyancy on the stability of a liquid pool heated from below a free surface at the upper boundary.

Significant activities continue in thermal convection in horizontal fluid layers heated from below. A number of studies were concerned with stability in such layers. A few treated post-stability flow and a surprisingly small number were concerned with phenomena at high Rayleigh numbers.

Stability of thermal convection with the boundary conditions imposed by solid walls of finite conductivity was examined [66F]. Another analysis [9F] considers the affect of sidewalls on stability in thermal convection. The critical Rayleigh number was experimentally determined using water in square cells over a large range of aspect ratios [29F]. The effect of a step change in surface temperature on stability in a horizontal fluid layer was analyzed [26F]. The convective instability with periodic variations of the vertical temperature gradient and the gravity field has been examined [21F]. Linear stability analysis has been applied to the stability of a fluid layer in which phase transitions occur [7F]. The critical Rayleigh number for the onset of cellular convection with lateral heating across a stably stratified horizontal fluid layer has been measured [10F].

The effect of a time periodic term on the temperature gradient was generally found [56F] to increase the magnitude of the critical Rayleigh number. The effects of rotation on the asymptotic stability of a horizontal fluid layer heated from below have been examined [31F].

The dependence of the post-stability flow pattern on the rate of heating, shape of container, and property variations with temperatue in the horizontal fluid layer heated from below have been experimentally studied [61F]. Interesting photos have been presented showing the instability of rolls in horizontal layers heated from below [8F]. The effect of large variations in the viscosity in the fluid layer on thermal convection as they might occur in the earth's mantle has been studied numerically [69F]. Experiments on free convection heat transfer with a density maximum within the fluid layer have been analyzed [64F]. A Mach–Zehnder interferometer has been used to determine the critical Rayleigh number in water which is cooled from below by an ice surface [67F].

Several studies have reported on natural convection in cavities which are vertical and relatively narrow, essentially a vertical channel formed between two parallel vertical plates. One study uses a transient approach to simulate the entrance region effects on stability in the flow when there is a temperature difference across the plates [24F]. Another study examined the stability in such a channel when internal volumetric energy sources are present [20F]. Experimental measurements were made of the overall heat transfer with natural convection through vertical plane layers of non-Newtonian fluids [15F]. The spacing to optimize the heat transfer from two parallel vertical plates at fixed heat flux is found to occur when the boundary layers from the two plates just merge [40F].

The critical Rayleigh number was determined above which turbulent flow occurs in a vertical rectangular cavity; the side walls were maintained at different temperatures [48F]. The Nusselt number for natural convection in an enclosed vertical layer is found to be just a function of the Rayleigh number over a large range of Prandtl number and for flow conditions from boundary layer development to turbulent transition [42F]. The transient behavior of flow in a rectangular cavity with two immiscible fluids has been studied [65F]. An experiment was performed on the transient natural convection in a vertical rectangular channel when one wall is suddenly heated [28F].

Flow and heat transfer in an open thermosyphon have been studied [35F] and a numerical analysis for such a system [23F] applies finite difference methods to obtain the heat transfer. The effect of inclination on a closed thermosyphon has been studied experimentally [34F]. The heat transfer and flow matters in a thermosyphon in a centrifugal force field have been studied [74F]. A study of the natural convection with internal energy sources in a closed vertical cylinder indicates that previous analyses which use integral techniques may be in error [72F]. In an open heated vertical tube, the height for fully developed flow is very large and one cannot ignore the transverse velocity in calculating the heat transfer in the developing region [13F]. Viscous dissipation reduces the temperature difference in laminar convection through a vertical circular tube and thus counteracts buoyancy effects [32F].

A number of studies are concerned with combined natural and forced convection heat transfer from horizontal cylinders. A laminar flow analysis examines both directly aiding and directly opposing flows [46F]. The ratio of the Grashoff number to the square of the Reynolds number was used to correlate results derived from combining pure forced and pure natural convection correlations to the case of mixed convection [33F]. The effect of parallel and counter flow on mixed convection were also described in another analysis [36F]. The effect of flow direction on the average heat transfer was studied [47F]. Measurements of heat transfer from small wires covered the complete range from pure natural to pure forced convection [18F]. Forced flow has been found to diminish natural convection heat transfer under certain conditions, in particular, with high viscosity fluids [73F].

Internal flows with combined natural and forced convection have been studied in the entrance regions of horizontal tubes [14F]. In horizontal tubes, natural convection effects may be important even at relatively low Rayleigh numbers [5F]. The combined effects of natural and forced convection heat transfer in a rotating circular tube have been studied [43F].

Several studies have been reported on combined natural and forced convection in vertical channels. The effect of pulsating flow on the heat transfer has been examined [17F]. A simplified model has been applied to combined natural and forced turbulent convection in a cylindrical tube [58F]. A slight lowering of the Nusselt number is found with viscous dissipation in a vertical concentric annuli [55F].

Stability of a horizontal Couette flow when heated from below has been analyzed to indicate the onset of thermal convection [12F]. The critical Rayleigh number for heating from below has been found to be dependent on the Reynolds number with laminar flow between two horizontal plates [2F]. For horizontal flows heated from below, the critical Rayleigh number was found to increase with Reynolds number while the onset of turbulence in the forced flow could be delayed by heating from above [51F].

Compressible flow has been analyzed to see what natural convection effects must be considered [22F]. Correlations have been presented for heat transfer from vertical rectangular fins including the effects of non-isothermal boundary conditions [1F]. A natural convection model has been applied to study the dynamics of electrolysis [4F]. The flow distribution has been calculated for natural convection in a macrocapillary [41F].

CONVECTION FROM ROTATING SURFACES

Dorfman's analysis of heat transfer in radial flow between a rotating and a stationary disc based on Reynolds analogy was extended [6G] to include frictional dissipation in compressible and incompressible flow. A turbulent Prandtl number of one and equal values of the diffusivities for momentum and heat were assumed. Nusselt numbers and adiabatic disc temperatures were calculated for Reynolds numbers between 5×10^5 and 5×10^6. A numerical analysis [7G] for the same configuration studied the effects of frictional heating, of disc temperature distribution, and of Pr number on Nu.

An analysis [9G] treats heat transfer in the laminar flow of lubricants between coaxial rotating cylinders including the effect of the temperature dependence of the viscosity. Experiments [10G] determined the velocity and temperature distribution as well as Nusselt numbers for turbulent flow in an annulus formed by two coaxial cylinders rotating at different speeds in the same and in the opposite directions for a Taylor number between 10^6 and 10^9. A stability analysis [3G] of natural convection in a thin vertical annulus rotating around its axis and heated from below revealed the existence of convection cells for Taylor numbers below 10^4.

Several papers treated heat transfer in rotating cylinders with a height-to-diameter ratio of order one. Laminar rotationally symmetric flow and heat transfer in such a rotating enclosure formed by two discs and a connecting cylinder with throughflow entering and leaving near the axis of rotation was studied [4G] by a numerical integration of the conservation equations. The results are presented in figures showing the velocity and temperature fields and the local Nusselt numbers. Laminar steady heat transfer in a vertical rotating cylinder of fluid heated from above was analyzed [5G]. The Tellurium method was used [8G] to visualize the flow of a liquid coolant in a closed cylindrical space with large length-to-diameter ratio with a heated wall rotating around its axis, and revealed the existence of numerous irregular eddies.

An analysis [2G] considers the temperature distribution inside a rotating sphere and in an unlimited fluid surrounding it a low Péclét and *Re* numbers. Steady state obtained by a heat source in the center of the sphere is postulated. Heat transfer at high Péclét number from a small sphere rotating in a simple shear flow was also analyzed [1G]. The result shows that with *Pe* going towards infinity, the Nusselt number approaches a value 9 or $4\frac{1}{2}$ times the value for conduction alone.

COMBINED HEAT AND MASS TRANSFER

Injection through various flow geometries with a high turbulence level free stream has been studied to simulate combustion chamber film cooling performance [11H]. Use of interrupted slots shows the importance of three dimensional effects that might occur in the cooling of gas turbine combustion chambers [16H]. Temperature and velocity fields downstream of secondary injection through circular tubes give information on the interaction of jets and a freestream as would be encountered in three dimensional film cooling [18H].

An analysis of two dimensional slot film cooling uses a two layer model downstream of the injection slot [7H]. Another two dimensional film cooling analysis for tangential injection at mass flow ratios less than unity [20H] has appeared, while a companion study extends the analysis to blowing rates as high as 3 [19H]. Finite difference procedures have been used [17H] to calculate wall temperatures with film cooling; a discussion of the application to cooling combustion walls is included.

A simple approximation yields the relative heat-transfer coefficient and parameters for separation at the surface with mass injection [15H]. Information on film cooling inside a tube can be inferred from gas concentration measurements following local injection of argon and helium [22H].

Film cooling following foreign gas injection through a narrow porous section along a wall into a Mach 3 flow has been correlated by adapting incompressible flow correlations [8H]. Secondary mass injection into a hypersonic flow decreased the heat transfer by more than 50 per cent downstream of the injection slot [21H]. An analysis indicates [13H] that for constant coolant mass flow, the effectiveness of local mass injection film cooling can be superior to transpiration cooling.

The results of previous experiments in transpiration cooling of compressible turbulent boundary layers have been correlated [4H]. A generalized method for calculating turbulent boundary-layer characteristics using transport coefficients has been applied to compressible turbulent boundary layers with combined heat and mass transfer [2H]. Good agreement between analysis and experiment, in particular at low blowing rates, has been found for transpiration cooling of a wedge in flows at Mach numbers of 16 and 20 [12H]. An analysis [3H] predicts the heat transfer at a porous wall with approaching flow. This might occur at the rear of a transpiration-cooled surface.

An analysis [14H] indicates the importance of viscous dissipation on streamline inclinations and surface pressure with surface mass injection into a high-speed turbulent flow. The effect of strong blowing into a supersonic laminar flow has also been analyzed [10H]. The effect of injection of light gases into a laminar supersonic boundary layer has been studied in great detail [1H].

The combined heat and mass transfer from an evaporating liquid layer on a flat plate with laminar gas boundary layer above it has been studied [5H]. Heat transfer for flow of an air–water mist past the heated cylinder has been studied [6H]. The heat and mass transfer with forced convection, under conditions when frost can occur, have been examined [9H].

CHANGE OF PHASE

Boiling

An experiment involving the rapid transient heating of a metal foil under water in which measurements of temperature, pressure, and heat flux were made with instrument response times $\leqslant 10\,\mu s$ has enabled new data to be obtained relevant to thermal explosions resulting from the mixing of molten fuel and coolant in an accident situation [8J]. Taking into account the heat content of the microlayer liquid, which was neglected by Cooper, this source of heat governs bubble growth [78J], although total microlayer evaporation requires a large amount of heat to be withdrawn from the solid. These findings, verified experimentally, explain why the thermal properties of the solid little influence bubble growth rate. Florschuetz and Al-Jubouri [25J] give generalized quantitative criteria for predicting the rate-controlling mechanism for vapor bubble growth. The minimum bubble departure diameter in nucleate boiling is empirically found [43J] to be $\bar{D}_{min} = 2{\cdot}7$ (Jakob number). In [63J] an expression is obtained for the frequency of vapor-bubble formation in boiling fluids from which known empirical relationships (fD = constant, etc.) follow as particular cases. For water, the bubble radius was found to vary as $(\text{time})^{\frac{3}{4}}$ rather than $(\text{time})^{\frac{1}{2}}$ as in theory, whereas the data for acetic acid were in agreement with the theory [69J]. Experimental values [87J] for superheat layer thickness for the incipient boiling condition lend support to Hsu's model for bubble nucleation.

The effects of translation on controlled vapor bubble growth are studied [68J] by means of a new similarity solution of the convective diffusion equation. Chapman and Plesset analyze thermal effects on the free oscillation of gas bubbles [14J]. The components of the damping: viscosity, thermal conduction in the gas, and acoustic radiation are all determined. Yaron and Gal-Or [88J] evaluate convective interfacial mass (or heat transfer) rates to/from ensembles of many spherical drops, bubbles, or solid particles (both uniform and size distributed) at high Péclét and low particle Reynolds numbers (as opposed to only a single drop or bubble in the ideal case of a completely pure system). Chiu [15J] describes unsteady vaporization of a liquid droplet exposed to a hot gas when Soret and Dufour numbers are finite.

The growth dynamics of a water droplet heated by a light pulse of one micro-second duration is described [46J]. Depending upon the radiant energy flux, either a continuous variation of droplet radius with time or a busting of the droplets was observed. Bode photographs very large drops [9J]. Drop photographs of steam on vertical copper and brass surfaces [45J] are compared with theory. A resulting simple approximation for the growth function agrees with the exact solution of Umur and Griffith with ± 1 per cent.

Recent data [62J] on uprising columns in near-critical, two-phase carbon dioxide suggest a diametral effect which contradicts earlier work of Abadzic and Goldstein. The beneficial effects of turbulization by bubbles on heat transfer (heat transfer increases up to 100 per cent over the natural convection condition) are limited by bubble departure frequency [10J]. A recent paper [44J] describes two computational schemes dealing with the rate of growth of vapor bubbles in a non-uniformly superheated liquid layer.

Trace amounts (60–500 ppm) of certain polymers dissolved in distilled water resulted in significant increases of nucleate boiling heat flux over that for water alone [28J]. The sound accompanying nucleate and film boiling is related to surface heat flux. The possibility of using an acoustic detection device to detect boiling caused by channel blockage in a liquid-cooled system is discussed [29J]. It is reasonable to expect that transient film and nucleate boiling processes occurring during the cooling of systems of sufficient thermal capacity can be assumed to be quasi-steady. Experiments [81J] provide direct experimental verification for both stable-film boiling and the minimum-film boiling point. Transient nucleate boiling heat rates for exponential heat inputs are well represented by steady state nucleate boiling correlations for periods greater than 5 ms [41J]. The heat-transfer characteristics of forced-convection quenching of spheres are significantly different than free-convection quenching [73J]. Experiments [27J] show that the vacuum pressure has little effect on the exponent (r) and significant effect on the constant (C_{sf}) in the Rohsenow pool boiling correlation. Stable nucleate boiling of water is observed [52J] in a rotating cylindrical annulus with heat fluxes up to 2·6 MW/m^2 although convective secondary flow cells and fluid temperature inversions were revealed.

The application of an electric field was found [51J] to have a sizeable effect on peak heat flux in saturated pool boiling—a result explained by a model of an electrically stabilized Helmholtz–Taylor hydrodynamic condition. The apparent viscosity of a small air bubble–liquid two phase mixture has been measured [34J] by a specially designed rotation viscometer. The gas volumetric method is used [72J] to measure temperatures in pool boiling on vertical evaporators because of space limitations and because average temperatures are needed. The authors of [61J] question how the critical heat flux changes on heating at saturation temperature when the circulation rate is markedly reduced. A new system in which principles have been applied to control a transition boiling process is described [58J]. It appears possible that the same principles can be applied in the control of boiling water reactors in such a way that fuel element burnout cannot occur. Nieberlein [55J] analyzes the preparation of high-modulus fibres by mass transport during film boiling.

The growth in the use of superconducting devices particularly large superconducting solenoids, has caused a subsidiary interest in the use of helium as a heat transfer agent [40J]. Helium II has several properties which make it unlike any other known fluid. For example, Helium II exhibits an unusually large capacity to transmit heat—having an effective thermal conductivity up to 3 orders of magnitude larger than pure copper at room temperature. In [35J], it is concluded that the Rivers and McFadden analysis offers a good method for predicting heat transfer during film boiling of He II.

Extensive heat transfer data is obtained from test sections designed for fully developed flow (straight inlets) and undeveloped flow (plenum sharp-edged inlets) [57J]. In the boiling regime, inlet hydrodynamics influences the transition from nucleate to film boiling over the entire test section while film boiling was influenced up to 8 diameters from the inlet. An equation that comprehends fully developed inlet flow, modified to correlate the plenum data, showed an average increase of 57 per cent in local heat transfer. Reference [59J] uses a liquid film flowing down an exposed heated surface which enables direct observation of droplet entrainment flow regimes as well as measurements of the film thickness. Dry patches may form during creeping flow of thin films of ethanol over a horizontal heating surface [56J]. The appearance of the dry spot is preceded by formation of Bénard-type convection cells. Hancox and Nicoll [30J] have extended the Zuber–Staub analysis on the prediction of nonsteady void and enthalpy profiles in forced convection water flow-boiling to include non-zero inlet subcooling. For a pool of two immiscible liquids boiling on a heated tube, significantly different results occur for the tube in the lower phase vs. the tube in the upper phase. Eighteen different cases are possible; no information is available for eight [74J].

Tubular coils are in extensive use in engineering devices. [3J] describes the results of critical heat fluxes with liquid flowing in tubular coils. with several geometries at $p = 2{\cdot}9$ bars. Correlation of available data [89J] yields verification of empirical burnout equations for water boiling in rod bundles. Crises in small-diameter channels with subcooled liquid flow may occur due to breakoff of circulation [79J] as a result of sharp incipient boiling of the liquid in the channel with resultant blocking by a vapor bubble. The mixture–vapor transition point in a horizontal tube evaporator is defined as the axial position where the last of the liquid is vaporized. Experimental evidence [86J] indicates that the motion of the transition point is of an oscillatory nature even for steady flow conditions. Forced convection nucleate boiling in vertical tubes is described by a total (turbulent) energy dissipation divided into three components: (1) dissipation for vapor bubble growth; (2) energy dissipated in the wall layer of the moving vapor–liquid mixture; and (3) energy dissipated in phase slip [23J]. Experiments [39J] on liquid helium flowing in a narrow channel reveal that the increase in peak heat flux with fluid velocity is more marked for turbulent flow than for laminar flow. Post-burnout heat transfer is the regime downstream of dryout point at positive qualities [11J] where the heat flux goes partly to the dispersed droplets and partly to the vapor. Reference [38J] studies heat transfer for pure film flow in a tube with ascending gas flow that causes a liquid film to move up the inner surface of the tube. The idealized slug flow model [60J] is satisfactory for the general determination of forced convective film boiling heat flux. The distribution of flow rates and flow stabilities in long, parallel channel evaporators are analyzed [2J]. Diabatic multirod subchannel data have been obtained [47J] in a 9-rod model bundle for operating conditions typical of a boiling water reactor. It is demonstrated that present subchannel computer programs are unable to predict the trends of the two-phase data regardless of the magnitude of eddy diffusivity mixing, thus indicating a fundamental problem in thermal–hydraulic modeling.

When a heated circular cylinder is rotated in a liquid at its saturation temperature, the thermal behavior falls into three distinct regions in terms of the critical rotating Reynolds number Re_c:(1) $Re < 0{\cdot}35\ Re_c$, heat transfer nearly independent of rotation; (2) $0{\cdot}35\ Re_c < Re < 1{\cdot}35\ Re_c$, heat transfer influenced by boiling and rotation; (3) $Re > 1{\cdot}35\ Re_c$, boiling does not occur [76J]. [24J] presents an analysis of heat transfer modes for a liquid boiling at a fin with constant cross section and compares the results with experiments with boiling water and F-113 on cylindrical copper rods. Properly applied thicknesses of insulation make it possible to maintain boiling over an entire fin surface—even when heat fluxes with densities four to six times the critical are transmitted through the fin base [66J]. Tape generated swirl flow in tubes substantially augments [7J] heat transfer in two-phase film boiling and minimizes the thermal non-equilibrium which is responsible for the relatively poor performance of normal boilers. The influence of Prandtl number on evaporating turbulent liquid films in the correlation of the heat-transfer coefficients of the usual power-law type is larger than expected [16J].

Condensation

[20J] presents an analytical study of the effects of noncondensable gas on laminar film condensation of a steam–air mixture undergoing forced flow along a vertical surface. The influence of the noncondensable gas is most marked for low vapor velocities and large gas concentrations. The nonsimilar character of the problem is especially evident near $x = 0$ where the convective behavior of the vapor boundary layer is highly position dependent. Moalem and Sideman [54J] give a general solution for bubble condensation, taking into account concentration gradients inside the bubble. Condensation rates for steam–air systems under interfacial suction, forced convection, or a combination of the two is remarkably improved [75J]. McBride and Sherman [53J] present an integrated solution for one-dimensional flow of a gas with equilibrium condensation of one component. The solution yields flow properties at a given nozzle area ratio without requiring a stepwise solution of the whole flow field downstream of the saturation point. Convergent channels improve condensation compared with channels of constant cross section [33J].

The Yih–Benjamin analysis of the stability to small surface perturbations of a thin liquid film flowing down an inclined wall is extended [6J] to include effects of evaporation (destabilising) and condensation. The breakup of thin liquid films flowing along a surface is due to hydrodynamic conditions at low flow rates (dry patches) and to the Marangoni effect (surface tension gradients) for rivulets [67J]. Shankar and Marble [71J] develop a kinetic theory of transient condensation and evaporation at a plane surface utilizing four moments in the Maxwell moment method.

An analytical study has been made of the condensation of vapor onto falling rivulets of liquid which are constrained in lateral width by vertical non-wetting (teflon) stripes on a flat metal heat transfer surface [12J]. The use of surface coatings to promote dropwise condensation and thus increase the rate of heat transfer has been the subject of many investigations—particularly polytetrafluoroethylene. Values of contact angles for fluids such as benzene, carbon tetrachloride, methanol, and aniline are presented [19J] which confirm the role of surface properties in controlling the mechanism of condensation on solid surfaces. In [36J] the results of drop condensation with fluorinated refrigerants with various promoters are given—whereby the deviation of the "water coat" theory of Nusselt in the range of small ΔT with partial mix or drop condensation is explained. Regularly spaced surface ridges have a small effect on condensation heat transfer for a pure vapor and this is magnified in the presence of non-condensables [13J]. Contemporary schemes for augmenting heat transfer frequently call for condensation in nonuniform body force fields or on various surfaces whose slopes change in a uniform gravity field. In [21J] expressions are developed for the condensate film thickness and local Nusselt number on arbitrary axisymmetric bodies that are identical with the Rohsenow–Nusselt expressions, except that they are based on an "effective gravity" and for the form of the body.

An analysis is given for calculating non-equilibrium, two-phase, gas-condensate mixtures in nozzles with allowance for coalescence and breakup of condensate droplets [4J].

Direct contact between steam and subcooled liquid occurs in many processes such as surface boiling equipment and new desalination devices. Destruction of a vapor bubble moving through a layer of subcooled liquid is studied photographically in [84J]. References [42J] and [82J] examine the path and depth of penetration of a liquid jet into a two-phase flow such as occur in a condensing ejector used in various power-generating facilities. [83J] analyzes condensation of steam emerging from an orifice into a cold fluid. The condensate droplets accelerate the external liquid layer which produces in the liquid a gradually increasing boundary layer consisting of the decelerated condensate and the accelerated liquid particles.

Two-phase flow

A few typical papers on two-phase flow are cited herein to provide a survey of areas of interest related to heat transfer. The principles of irreversible thermodynamics are applied to the propagation of an acoustic wave in a two-phase medium [65J]. Expressions are obtained for determining the speed of sound in a vapor–liquid medium as a function of the quality and degree of nonequilibrium of various relaxation processes accompanying the propagation of acoustic waves. D'Arcy [18J] finds two distinct speeds. Both propagation speeds have been observed in experiments. Although both modes are theoretically possible at all voids, in practice only one mode is observed at any given void. [37J] deals with propagation of weak disturbances and heat transfer in two-phase media with phase transitions. Henry and Fauske develop an advanced model of two-phase critical flow of one-component mixtures in nozzles, orifices, and short tubes that incorporates the best available data to determine reasonable correlations for heat and interfacial mass-transfer rates [32J]. [26J] suggests that anomalous upstream choking conditions (as quality approaches zero) can occur generally with the engineering computational modes of two-phase pressure drop and that its occurrence is a result of inaccurate assumptions implicit in the models. In [31J], a method for computing two-phase gas–liquid flow rates through throttling devices is presented ("method of equivalent densities") where only the properties of the throttling device with single phase flow are used.

Theoretical analyses of the central region of dispersed annular flows are restricted due to lack of data on local conditions. Summaries of such studies are given in [22J].

Bankoff [5J] analyzes minimum thickness of a draining liquid film. Prisnyakov [64J] deals with draining of a two-phase fluid from a tank. Charts are given which facilitate computation of transient conditions in thermal power plants. A semi-empirical theory of slug flow pressure losses in horizontal and inclined tubes require *a priori* knowledge of the slugging frequency [80J]. Mass transfer in two-phase flow studies has not been so popular as heat transfer investigations but now is attracting more attention [17J] and [85J]. [1J] presents results of measuring the electrical conductivity and the effect of thermal conductivity of two-phase sodium vapor flow in a flat channel with $T \approx 1050°K$. A description of experimental equipment for investigating steam–water nozzles is given in [77J], along with a device for measuring the two-phase flow momentum to within $\pm 1{\cdot}5$ per cent.

By neglecting the thermal capacity of the advancing phase and assuming saturation temperature for the other phase, a simple theory is developed for periodic freezing and melting of water [70J]. Lebedev *et al.* [48J–50J], author a series of papers on the kinetics of ablation of ice water from porous cermets. A remarkable feature is the high temperature of ablating ice in porous ceramics (22°C ice superheat) as compared with 2–5°C for ice heated by radiation and 8°C for direct contact.

RADIATION

Radiation in participating media

A number of papers account for the nongray nature of radiation in participating media. A linearized differential equation for the radiative heat flux is obtained for a nongray gas in local chemical equilibrium and slightly disturbed radiative equilibrium, and this equation is applied to radiatively driven acoustic waves [18K]. Considering the interaction heat transfer problem involving conduction and radiation in a nongray medium, numerical results are obtained for CO and CO_2 [20K]. A study of the nongray radiating flow about smooth symmetric bodies at speeds from 10·7 to 15·2 km/s at an altitude of 61 km shows that the radiative heating distributions depend strongly on whether the primary source of radiation is the entropy layer or the flow external to the entropy layer [44K]. The continuum radiative flux from a nongray, nonisothermal stagnation shock layer composed of an atomic gas is calculated assuming that radiation and fluid dynamic effects can be uncoupled [42K].

Charts for the total emissivity of water vapor for temperatures between 600 and 2500°K are derived from long-path spectral data available in the literature [13K]. The study of infrared radiation properties of SO_2 reveals large discrepancies with Hottel's results. Possible causes for these discrepancies are discussed [15K]. Considering radiation properties of hot gases, the applicability of approximate methods of the radiant transfer theory is examined [9K]. A survey of primary and average radiative properties of solids is presented [38K].

Problems associated with simultaneous conduction and/or convection and radiation have been extensively studied. It is shown that the two-term Taylor series expansion of the emissive power provides an accurate and useful method for the prediction of the net heat transfer for combined radiation–conduction problems [5K]. The two-flux model is applied to the equations of transfer in order to study heat transfer by conduction and radiation in absorbing and scattering materials [7K]. With an approximate analysis for transient heat conduction with radiation in a slab, the temperature, conduction, and radiation heat fluxes can be predicted without resorting to lengthy numerical analysis [2K]. The heat transfer by combined infrared radiation and conduction in a layer of water vapor is analyzed by using a potential method and measured values of spectral absorption in the temperature range between 600 and 3000°K [16K]. In connection with investigations of solidification of semi-transparent materials by conduction and radiation, it is shown that radiation appreciably affects the temperature distribution in the solid phase [26K].

The nonlinear interaction of thermal radiation and free convection of an absorbing–emitting gray gas is calculated for a boundary layer in front of a vertical, heated plate which is assumed to be black. Results for various ratios of wall to gas temperature are compared with linearized asymptotic solutions [36K]. An investigation of laminar convection of a radiating gas in a vertical channel demonstrates that radiation decreases the temperature difference between the gas and the wall, thereby reducing the influence of natural convection [24K].

An analytical study of the influence of optically thin radiation on heat transfer in the thermal entrance region of narrow ducts is presented [25K]. The question is clarified how radiative emission affects the flow in the shock structure of a low-density hypersonic flow around a blunt body [49K]. The jet flow of a radiating gas is studied analytically and the effect of the inhomogeneity of the radiation field on the jet flow is described [23K]. In connection with heat transfer studies from a rocket exhaust jet, a mathematical model is adopted which considers the inviscid flow field of a high temperature, optically gray and thick jet exhausting from a two-dimensional nozzle into a low temperature quiescent medium [35K]. A fluid flowing in a channel is heated by combined radiation and convection from the outside. Its temperature distribution is found by a linearizing transformation which reduces the nonlinear boundary condition to a boundary condition of the third kind [34K].

The calculated distribution of radiant heat on the water-cooled surfaces of a boiler surface which depends strongly on the flow pattern of the burning gas, is in qualitative agreement with measurements [30K].

The effect of absorbing media on radiative transfer found considerable attention during the past year. Temperature distributions and heat flux are calculated for a gray absorbing gas in radiative equilibrium, bounded by directional walls maintained at different temperatures [55K]. Radiant heat transfer between coaxial cylinders separated by an absorbing and radiating medium with heat sources is investigated, and limitations of the analytical solutions are established from a comparison with published numerical results [45K]. A CO_2–N_2 laser beam is passed through a CO_2 absorption cell. Local gas temperatures measured near the edge of the laser beam indicates very strong absorption heating within the convection column at lower cell pressures [17K].

In connection with the accident of the Apollo 13 mission, it has been shown that in cryogenic oxygen systems employing a central heater, infrared radiation prevents overheating of the heater and reduces temperature gradients in the oxygen by supplying heat to the container wall [12K].

Calculations of the spectral absorptivity of carbon particles in flames indicate that the integral emissivity of thermally radiating sooty flames depends very strongly on the size of the carbon particles in the flame [10K]. The extinction parameters of submicron particles dispersed in hydrogen atmosphere in a wavelength range from 1200 to 6800 Å and temperatures up to 2170°K are approximately 50000 cm^2/g for carbon, approximately 20000 cm^2/g for tungsten, and approximately 65000 cm^2/g for silicon. This parameter increases with increasing pressure and temperature and reaches for submicron tungsten particles at 100 atm and 2300°K a value of 10^5 cm^2/g [56K].

Two new approximate expressions are suggested for the shape factors for the sides of a parallelepiped separated by an absorbing medium [19K].

The effect of surface films on emission and absorption of radiation has attracted increasing interest. Evaporated aluminum coated with double layers of Al_2O_3 and silicon oxide produces films with low solar absorptivity (α) and high total normal and hemispherical emissivities (ε_N and ε). With such film combinations, which are extremely stable during UV irradiation, α/ε values of less than 0·2 have been achieved [27K]. The film thickness of transparent and slightly absorbing dielectric films and other optical properties of the film and of the substrate are derived from measurements of the monochromatic, specular reflectance of linearly polarized light at various angles of incidence using a He–Ne laser as light source [46K, 47K]. The results of a study of the effect of homogeneous thin films on the emittance of a metal substrate lead to the general conclusion that fine-scale roughness in the oxide layers on metal surfaces cause a reduction in emittance relative to that of a homogeneous oxide layer of equivalent thickness [14K].

Fluoride-overcoated aluminum can be useful as reflector to wavelengths as short as 500 Å [33K]. Studies of the emissivity and absorptivity of various ash deposits on boiler surfaces indicate that the ash properties deviate from gray body behavior revealing a pronounced temperature dependence [1K, 41K].

The normal-mode-expansion technique is applied to obtain a semi-analytical solution for the angular distribution of radiation at any optical distance within a linearly anisotropic-scattering, absorbing, emitting, nonisothermal, gray medium between two parallel reflecting boundaries [6K]. A theoretical treatment of the thermal radiation in a randomly inhomogeneous medium shows that spatial dispersion and scattering processes due to macroscopic inhomogeneities of the medium play an important role in the formation of a thermal electromagnetic field [48K]. Using a simplified model of a metalized rocket exhaust plume, the importance of anisotropic scattering and search light effects on the angular distribution of thermal radiation is demonstrated [53K]. A simple model for thermal radiation, based on the Milne–Eddington approximation, has been successfully applied to predict heat transfer in an axially-symmetric pulverized-fuel flame [22K].

The Patankar–Spalding finite difference solution method has been modified to account for the transport of radiant energy in a turbulent optically thin boundary layer [21K]. Several advanced methods are discussed suitable for calculating radiation transport in ablation-product contaminated boundary layers [43K]. A method for computing the nonequilibrium radiant emission from near-equilibrium shock layers provides adequate predictions of the radiant emission [40K].

Results of radiative heat flux calculations in a cylindrical furnace using the Monte Carlo method compare favorably with previous calculations for identical conditions using the classical interchange method for the radiative terms [52K].

Surface radiation

The spectral emissivity of molybdenum and aluminum oxide was measured [39K] in the temperature range from 1000 to 1500°C. A simplified formula was derived [37K] which is useful for experimentally determining the reflective properties of solids for oblique radiation. An analysis [3K] based on wave optics studied the radiative properties of surfaces with a surface roughness in the form of sinusoidal waves irradiated by plane monochromatic radiation. The transmittence was found to reach a maximum when the wavelength of the surface roughness is equal to the wavelength of the irradiation. Numerical results are presented for dielectric plates.

Several papers present analyses for enclosures filled with a non-participating medium. A comparison [32K] of an analysis with experiments for a cavity formed by two specular-diffuse surfaces and one bi-directional surface irradiated by collimated radiation shows that large errors can result in the analysis unless the directional character of the surface properties is properly considered. The integral equations were solved [29K] to study the radiant energy interchange between two grooved surfaces forming a wedge.

The Monte Carlo method was applied [28K] to study the efficiency of hemiellipsoidal collectors with the radiant source in one focus and the sink in the other and of hemispherical collectors used as an approximation. For the ellipsoidal collector, the radius of the sink has to be at least twice the radius of the source to obtain good collection efficiency. The method by Surinov to solve integral equations numericaally was used to study the radiant heat-transfer characteristics in rectangular chambers [54K] and for an open cylindrical space [4K]. Transfer functions for two coaxial ringshaped surface elements are presented in graphs [8K]. They are useful in studying radiative exchange for surfaces of revolution. Measurements of the radiant heat transfer between a plane strip and a cylindrical enclosure [51K] established the fact that the formula for two concentric cylindrical surfaces serves as a good approximation. A script-f matrix formulation for enclosures with arbitrary surface emission and reflection characteristics is derived [11K] and applied to a number of examples.

The results of an analysis [50K] determining the radiant flux from a porous wall heated internally by a gas and cooled by radiation are presented. Yearly average concentration factors of 2 or higher for solar irradiation are obtainable by a simple V-shaped trough formed from specularly reflecting surfaces with the sink located at the base of the trough [31K].

LIQUID METALS

The surface renewal and penetration model was used [7L, 8L] to calculate turbulent heat transfer for liquid metals in tube flow. Previous analyses with this model had to be modified by consideration of a temperature drop of the spherical eddies on their way to the wall. The magnitude of those was obtained from heat-transfer relations on a sphere.

An analysis [5L] considers heat transfer from a liquid metal flowing normal to a solid heat generating cylinder, assuming potential flow and heat transfer by conduction only. The Péclét number was varied between 0·9 and 11·3 and the ratio of conductivities of the fluid and solid from 0·31 to 3·1. Good agreement with the analysis by Grosh and Cess was obtained for a uniform wall temperature. Turbulent heat transfer for in-line flow of a liquid metal through rod bundles was calculated [3L] considering heat conduction only. The heat flux at the wall surface was prescribed as uniform axially with a uniform temperature circumferentially or as uniform in all directions. The effect of cladding was also investigated. The results are presented in graphs and in the form of equations. Experiments [1L] on heat transfer from rod bundles placed at angles $\alpha = 30, 60, 90°$ to the incident liquid metal flow at Péclét numbers from 10 to 600 resulted in the equation:

$$Nu_{\infty} = \sin_{\alpha}^{0.4} Nu_{90}.$$

Heat transfer to pool-boiling mercury from horizontal cylindrical heaters was measured up to heat fluxes at which the temperature difference ΔT started to increase rapidly. These limiting fluxes could be satisfactorily predicted through burnout correlations by Noyes and Addoms [9L]. Experiments [4L] studied critical boiling heat fluxes in potassium flowing through a non-uniformly heated pipe. The vapor quality at the point of boiling crisis was 0·5–1. The relations available for uniform heating described the qualitative behavior of the critical heat fluxes. Their values, however, depend on the degree of non-uniformity of the heating.

Previously established relations were verified by an experimental study [6L] of heat transfer in condensation of potassium vapor in a horizontal tube. The condensate film has a minor effect on heat transfer. Nucleation in homogeneous liquid sodium induced by nuclear radiation was analyzed [2L] based on a "thermal spike" theory. The evaporation of a liquid metal droplet suspended by an electromagnetic field in vacuum was studied [10L] in view of the possible application for evaporation processes for chemically active metals.

LOW-DENSITY HEAT TRANSFER

From measurements of low Reynolds number heat transfer from fine platinum wires to helium and helium–air mixtures, the slip parameter was inferred as a function of helium concentration [12M]. Measured heat transfer results at the stagnation point and along the surface of a hemisphere-cylinder in a hypersonic rarefied flow were employed to test the applicability of theoretical predictions [3M]. Expressions have been derived for the radiometer force and the thermomolecular pressure difference in a binary gas mixture as a function of pressure from the free molecule regime to the continuum regime [6M]. Temperature jump effects were included in an analysis of the thermal transient which occurs when a gas and a solid at different temperatures are brought into contact [1M]. Semi-empirical equations, derived from models based on simplified kinetic theory, are proposed for bridging the gap between free molecule and continuum flows. Equations are presented for heat transfer, surface shear, drag, lift, and pressure distribution [8M].

The effect of surface roughness on the accommodation coefficient was correlated with the tangent of the angle which corresponds to the average slope of the lateral side of the microroughness [11M]. A careful formulation was made for the evaporation of a solid into vacuum, taking kinetic theory aspects into account. It was found that the vapor pressure at the solid surface is less than the saturation vapor pressure corresponding to the temperature of the solid [7M]. Sublimation–dehydration is a process by which biological substances are dried in the frozen state in a vacuum chamber. In analyzing the process, the flow of the sublimed vapor through the dried region of the product was considered for the free-molecule, transition, and continuum pressure ranges [5M].

A variational principle based on the integro-differential form of the linearized Wang Chang–Uhlenbeck equation was employed to obtain a closed form expression for the heat transfer through a polyatomic gas contained between parallel plates; the results are valid for all degrees of rarefaction and depend parametrically on the thermal accommodation coefficients [4M]. Nordsieck's Monte Carlo method of evaluating the Boltzmann collision integral has been used to solve the non-linear Boltzmann equation for the heat-transfer problem between two plates at different temperatures; solutions covered the Knudsen number range from 0·1 to 100 [13M]. The linearized Boltzmann equation was solved by a two-stream moment method to yield the flow through an infinite planar slit [2M]. The hypersonic near free molecule flow over a sharp leading edged flat plate with a small thermal accommodation coefficient was analyzed by means of the Willis integral iteration method of solution of the BGK equation; with decreasing values of the accommodation coefficient, the influence of upstream collisions was reduced [9M]. Plane Couette flow and heat transfer have been studied using the non-linear BGK model along with the full-range moments method [10M].

MEASUREMENT TECHNIQUES

An amplifier has been designed [5P] to be used with thermocouples to measure rapidly varying (periods of about 0·01 s) temperatures. The simplified calculations to find the magnitude of the error when measuring a pulsating temperature have been presented [21P]. The correction of thermocouple errors due to variations in temperature along the thermocouple wires has been calculated [34P]. Errors induced when measuring surface temperatures from thermocouples pressed against the surface have been described [43P].

A thermometer based on nuclear quadrupol resonance has been constructed and found to be accurate to 0·003°C at liquid nitrogen temperature [26P]. Different techniques used to measure the temperatures of leaves are compared [27P]. Measurement of the elongation of the test section was used to infer the surface wall temperature and then from this the heat transfer coefficient was obtained [31P].

Experiments confirm a model for the measurement of the surface temperature of a deflagrating solid using a thermocouple [37P]. A temperature probe has been designed for use within furnaces [3P]. Gas temperatures in a gas particle flow have been measured using multiple thermocouples to subtract out the effect of the particles [14P].

From knowledge of the recovery factor on a circular cylinder, a thermocouple probe was used to measure total temperature over a large range of flow conditions [6P]. An enthalpy probe has been used [4P] to measure total enthalpy of a flow up to 98 MJ/kg.

An optical pyrometer has been designed for measuring the temperature of thin moving films in the range 900–1400°C [10P]. The error in a pyrometer due to changes in the temperature of the surrounding medium has been calculated [38P]. Pyrometers for use at temperatures as low as 40°C have been described [39P].

A moving thermocouple has been used for rapid measurement of thermal conductivity of solids at temperatures of 300–1200°K [15P]. A periodically heated probe is used for the simultaneous determination of thermocouple conductivity and diffusivity of porous materials [2P]. A calorimetric installation has been designed to measure emissivity of metallic surfaces over a range of approximately 77–473°K [32P].

A multi-slit Schlieren system using cylindrical lenses yields a Schlieren system with increased versatility [20P]. A holographic system using two laser wavelengths generates interferograms with a range of sensitivity [41P]. Brillouin scattering and optical interference have been suggested [8P] as techniques to detect boiling in pressurized water reactors. The reduction of sonic velocity with voids has been suggested as a technique to determine the initiation of boiling in sodium [9P].

Experiments [7P] show promise for studying multi-component flows with a flow visualization technique using chemiluminescent radiation. The thickness of thin liquid boundary layers has been measured with an optical technique using a chemical indicator [36P]. Boundary layer transition data in high speed flow obtained from temperature-sensitive paint agree with measurements obtained from wall thermocouples [29P]. Application of hydrogen bubble techniques to flow visualization in closed conduits has been demonstrated [33P].

The constant temperature hot wire anemometer has been analyzed to determine static and dynamic response characteristics including the effect of the electronic analyzing equipment [35P]. Presence of a velocity gradient along a hot wire tends to give velocity readings less than the true value at the center of the wire [18P]. Shear also causes a decrease in the sensitivity to velocity fluctuations.

The effect of flow angle on the readings from total pressure tubes was experimentally determined for subsonic flow. High stream turbulence was found to diminish considerably the angle to the flow at which the instrument reading differs from the total pressure [12P]. Tables are presented [24P] to simplify the calibration of Preston tubes for measuring wall shear stress. A thermistor anemometer has been used for precision measurement of air flows from 5 to 100 cm/s [28P]. The limiting frequency response of wall heat or mass transfer probes used to measure a fluctuating velocity gradient has been determined [17P].

An analysis for a laser–Doppler anemometer defines the regions for which the Doppler signals are received as well as the resulting spectrum bandwidths and amplitude [1P]. Another analysis predicts signal that would be obtained in a turbulent flow [40P]. A comparison of various optical geometries for laser–Doppler measurements has been made [13P]. An analysis of the key parameters in back-scatter measurements of a laser–Doppler system for atmospheric studies has been presented [16P].

A number of experiments have also been reported on measurements and applications of laser–Doppler anemometry. Fluid velocity gradients have been determined in liquid flows on solid surfaces [19P]. Low frequency pulsating laminar flows have been measured [11P]. The heterodyne-feed output of a photomultiplier tube to a TV screen provided optical read-out of a laser–Doppler system [22P]. Improved techniques for analysis of Doppler line profiles from a Fabry–Perot interferometer have been described [23P].

Fluctuations in the scattering of a laser beam passing through a high temperature jet exhaust gave information on turbulent fluctuations in the jet [25P]. A Doppler holographic technique has been used [30P] to measure and visualize a seeded flow. A photomicrographic technique has been used to measure liquid velocities very close to a fluid–solid interface [42P].

HEAT TRANSFER APPLICATIONS

Heat exchangers

Experiments [14Q] investigated the influence of non-uniformity of heat transfer on the effectiveness of round fins. The optimum shape of a fin for the condition that nucleate, transition, and film boiling occur simultaneously on its surface can be approximated [2Q] by two cones touching base to base. A liquid fin similar to the heat pipe is proposed [10Q] for heat transfer equipment. The results of measurements [8Q, 12Q, 16Q] are reported for a number of finned surfaces. A method is proposed [11Q] to account for conduction effects in surfaces with regular roughness elements used in nuclear reactors.

Equations which well approximate the Nusselt numbers for staggered and in-line tube banks have been proposed [6Q]. Experimental results [19Q] have been reported for tube bundles with spiral fins. The effect of non-uniformity and fluctuation of the flow on heat exchanger efficiency was analyzed [18Q]. A design method for heat exchangers having heat-transfer coefficients which vary along the flow path was found [13Q] to be low by 10 per cent under some conditions. Heat exchangers for gas turbine installations [1Q, 3Q], for oil coolers [15Q], for rotating heat exchangers for air conditioning equipment [9Q], as well as for a concentric sphere heat exchanger [4Q], have been investigated. Improvements to the computation of regenerative heat exchangers have been discussed [5Q, 7Q, 17Q].

Aircraft and space vehicles

Ablation, heat shield performance, and other thermal protection systems for space missions, especially in connection with space shuttle, are discussed in many papers. Results of heat-shield ablation studies at superorbital re-entry velocities demonstrate that doubling of the total (convective + radiative) heating rate can produce a six-fold increase in ablation rate [5R]. For an evaluation of the effects of surface roughness on heat transfer to ablating bodies, a simple calculation procedure is described which may be readily adapted to existing computer routines for smooth wall heating distributions

[9R]. Theoretical ablation solutions for the Apollo heat shield material are compared with data obtained in an arc-plasma tunnel [4R]. The results of a study of gas phase chemical reactions on heat transfer to a charring ablator may be used for the evaluation of heat transfer shield performance during Apollo re-entry [23R]. Experimental investigations of the performance of a charring ablator under transient and steady-state convective and radiative heating reveal that transients in material response in an increasing heating environment results in accelerated material degradation [39R]. Solution of the equations describing the nonequilibrium flow of pyrolysis gas products through the char layer of an ablative heat shield are presented [2R]. Ablative material tests with transient heating using a 10 MW arc-plasma facility allow simulation of ballistic re-entry conditions; and the results compare, in general, favorably with theoretical values [25R]. An arc driven channel test device is described which represents a valuable and versatile tool for examining the ablation characteristics of materials in a turbulent flow re-entry environment [32R].

Hypersonic wind tunnel tests of conical camphor models extended the crossflow-hatching angle vs. edge Mach number correlation as well as the curve showing pattern wavelength varying inversely with local pressure [44R]. The understanding of the surface patterns of ablating bodies can be greatly enhanced by using a simulation technique in which the models coated with wet paint are exposed to a water jet [29R]. The ablation surface patterns and the resulting roll torques have been studied using conical models covered with various low temperature ablative materials in a hypersonic wind tunnel [43R]. Experimental results showing crosshatched ablation patterns seem to indicate that the driving temperature dependence of the pattern size is characteristic of liquifying ablation materials [35R].

Numerical results for the transient response of ablating axisymmetric bodies compare favorably with exact solutions [36R]. For calculations of the transient thermal response and ablation of non-charring heat shields and nose tips, a versatile computer code is developed [28R]. A calculation of the overall erosion rate (mechanical + thermochemical) of a silica-nylon-phenol material produces satisfactory results with respect to local environmental conditions if a simple phenomenological expression is utilized [17R]. Model fabrication techniques and instrumentation for the study of the boundary layers in front of low-temperature subliming ablators are described [20R].

Thermal design for spacecraft makes extensive use of heat shielding and multilayer insulation exploiting the fourth-power temperature dependence of radiation heat transfer. For such a radiation dominated heat balance, an iterative method is proposed which eliminates instabilities of previously used numerical techniques [7R]. An analysis for steady, two-dimensional transpiration cooling with an incompressible coolant, applicable to the nosetip of a space vehicle, demonstrates that two-dimensional effects in coolant flow are important for assessing internal coolant distribution and for achieving adequate nosetip protection [31R]. Measurements of local pressure and heating rates on the Apollo command module during entry from orbits of Apollo missions 1 and 3 show that pressure measurements compare well with wind tunnel results [19R]. The thermal performance of multilayer insulation systems is strongly affected by lateral heat transfer in the spacer materials [15R].

In connection with space shuttle, swept- or delta-winged configurations have been proposed. The maximum stagnation line temperature of the leading edge of a 60° swept wing for an equilibrium glide entry is approximately 1470°K at an altitude of approximately 70 km [10R]. Consideration of chemical nonequilibrium effects on the boundary layer should be included in the design of a space shuttle thermal protection system utilizing coated metals and alloys which inhibit surface recombination of dissociated species [1R]. If interactions of atomic oxygen with shuttle orbiter surfaces can be suppressed, a substantial improvement in operational capability and survivability would be obtained [34R]. In connection with space shuttle, minimum heating entry trajectories can be flown with very low aerodynamic loads [26R]. Wind tunnel tests associated with space shuttle considering a lifting entry vehicle of simple geometry produce data on boundary layer transition and turbulent heat transfer [45R]. The capabilities and available technologies of regenerative cooling systems is discussed for application to space shuttle engines [42R]. The influence of heat-rejection radiators on space nuclear power system mass has been studied as a function of radiator mass/surface area [8R].

Studies of vortex-induced heating to the Lee side of slender wings in hypersonic flow show the feasibility of reducing the effect by properly contouring the leading edge planform [40R]. A similar study of hypersonic Lee-surface heating on delta wings shows that this effect can be practically eliminated by aligning the apex region with the free stream [30R].

The effect of film cooling on nozzle performance was evaluated for a conical plug nozzle at Mach numbers from 0 to 2·0 [16R]. A convenient correlation of the local heat-transfer rate with the local surface pressure for blunt cones at various angles of attack is derived and its usefulness is demonstrated [41R].

A few papers deal with problems associated with future space missions. Planetary entry body heating rate measurements in air and Venus atmospheric gas agree in the temperature range from 12 to 15000°K with theoretical uncoupled convective heating summed with isothermal radiative flux reduced by a radiative cooling factor [21R]. Heat transfer calculations for the radiation loads on a Venus entry vehicle reveal that the important radiators are the fourth positive group of CO, the continuum from carbon, and the line emission from neutral carbon [12R]. The heating-rate histories and heat-shielding requirements for three different-sized Jupiter atmospheric probes have been studied; and the results indicate that for half the probe's weight devoted to heat protection, a graphite-class heat shield can function reliably at heating rates on the order of 100 kW/cm^2 [37R]. A study of the effective Martian sky temperatures for inclined plates shows that these temperatures increase only slightly with increasing plate inclination [38R].

Silicon solar cells covered with fluorinated ethylene propylene (FEP) have been exposed to a simulated micrometeroid bombardment and they seem not to degrade as quickly as did the Mylar or Kapton covered CdS cells [24R].

The honeycomb-porous bed concept is shown to be an effective means for solar air heating. The cost per useful energy collected was minimized for values of wall coating thickness between 0·4 and 0·8 mil, cell depth to spacing ratios between 4 and 10, and cell width to spacing ratios between 7 and 10 [18R]. An analysis of the efficiency of solar energy absorption of a system consisting of a honeycomb structure affixed to a collecting base surface is based on a two-band model (solar and infrared) [33R].

A full-scale engine test at average gas temperatures of 2750–2800°F demonstrates that transpiration cooling of turbine blades is an effective means for achieving reliable and efficient gas turbine operation in high gas temperature environments [27R]. Liquid rocket engine exhaust plumes have been analyzed and comparisons with available experimental data show satisfactory agreement [13R].

The effects of density, pressure, and temperature on the heat transfer in Apollo 11 fins are determined [11R]. Experiments with a spherical particle 2·5 mm dia. demonstrate that heating of the particle appreciably increases the aerodynamic drag as compared with isothermal conditions, particularly in the low Reynolds number range [6R].

Heat-transfer studies to an airfoil in oscillating flow reveal at large angles of attack, including those associated with stall in steady flow, a strong periodic starting vortex shed from the leading edge causing a dramatic reattachment of the flow and an increase in local Nusselt numbers by as much as a factor of five [22R].

Gravity-induced free convection greatly alters the melting interface profile and the temperature profiles within the phase change material. For a proper description of these effects, a combined conduction–convection heat transfer and fluid dynamics model must be developed [3R].

Equilibrium composition and radiation of metallic plasmas produced by hypervelocity impact are calculated for pressures of 1, 10 and 100 atm and temperatures from 5000 to 40 000°K [14R].

General

A group of papers considers the heat pipe. Consideration is given to calculation procedures [7S, 24S] of the steady state and dynamic behavior and of the temperature control [16S]. A second generation of heat pipes provides arteries for the flow of liquid from the hot to the cold end [5S, 7S]. Cryogenic heat pipes using liquid nitrogen in a temperature range from 78 to 90°K have been developed [5S]. The effect of Meniscus radius of the wicking material on the pumping head is investigated [21S] and maximum axial heat fluxes of sodium and potassium heat pipes have been measured [13S].

Experimental data are presented [11S] for various methods of gas turbine blade cooling obtained in a cascade and an analysis [17S] of the effectiveness of transpiration cooling of turbine blades includes the effect of surface roughness and coolant distribution.

The temperature field and heat transfer in the fuel elements of a Bor-60 nuclear reactor were studied [19S] on an electrically heated model. Studies concerning fast breeder reactors considered incidents of sodium boiling [15S] and coolant transients in a gas-cooled reactor [4S].

The temperature field in finned tubes for furnace walls were obtained [12S] by electrical modelling. The performance of air-cooled honeycomb matrices for solar heaters was measured [8S] and analyzed [10S]. Instruments for the measurement of solar-optical properties of glazing materials [14S] and the effect of reflective coatings on architectural glass [23S] were investigated. Two papers treat the formation and maintenance of thermoclines in temperate lakes [20S] and in the Red Sea [6S]. The thermal stimulation of an oil reservoir by a moving fire front was studied [1S] in an oil field in the Krasnodar region. The temperature field created by arc welding of a circular disk [18S] and the effect of oscillating flow of the molten material during electron beam welding was analyzed [22S]. Solutions were obtained for the equations describing heat transfer in the cooling and solidification of thermoplastic materials [9S] and of fibres [3S] in the formation process. Air cooling of large scale computer systems is discussed [2S].

PLASMA HEAT TRANSFER

Heat transfer studies in ionized gases reported during the past year refer to fundamental investigations, as well as to applications. An analysis of radiation energy transfer within a nonisothermal air plasma shows that for higher densities, the optically thin, optically thick, and differential approximation results differ significantly from the general solution over a large range of surface spacings [6T]. A computer study of nonequilibrium excitation in recombining nitrogen plasma nozzle flows shows that there is a severe and unexpected departure from excitation equilibrium above a chamber pressure of 10 atm [1T]. Temperature and electron density distributions in an atmospheric pressure nitrogen plasma jet have been measured, and an estimation of the Prandtl numbers gives values ranging from 0·06 to 0·75 [7T].

In an attempt to correlate data of electric arcs in transverse magnetic fields with dimensionless parameters, systematic deviations of the predicted behavior are observed superimposed to the relatively large random scatter of the data points. The author claims that these deviations are associated with heat-transfer effects [9T]. Experimental results obtained from a transpiration cooled electric high intensity arc show large discrepancies with analytical predictions which are mainly attributed to turbulent-flow components in the transpiration cooled constrictor tube [4T]. An empirical correlation for average Nusselt numbers has been determined for argon and nitrogen plasmas passing through a water-cooled calorimeter with internal, longitudinal fins [5T]. Heat transfer measurements to the insulator wall of a linear MGD accelerator agree within experimental scatter with a Hartmann boundary layer analysis [2T].

Anode heat fluxes between 19^4–10^6 W/cm^2 have been found in pulsed arcs using various combinations of anode materials and working gases [8T]. Film cooling of the anode of a plasma generator results in a minor improvement of the gas heating efficiency compared with similar purely water-cooled anodes [3T].

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