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HEAT TRANSFER—A REVIEW OF 1973 LITERATURE

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INTRODUCTION

THIS review surveys the field of heat transfer, the results of which have been published during 1973. The number of papers published during that period was such that a selection only can be included in this review. A more complete listing is contained in the Heat Transfer Bibliographies published periodically in this journal.

Several conferences have provided valuable information on heat transfer processes. The 14th National Heat Transfer Conference, held 5–8 August at Atlanta, Georgia, presented papers on various heat-transfer processes in seventeen sessions. A Processes Equipment Problem Forum dealt with reboilers, condensers, and tube-sheet joints. Invited lectures by K. Timmerhouse on "Heat transfer at cryogenic temperatures", and by J. Davis on "The national energy program", rounded out the conferences and three film programs offered visual insight into heat-transfer processes. The presented papers are available in preprint form from the American Society of Mechanical Engineers or the American Institute of Chemical Engineers.

The 1973 International Seminar, organized by the International Centre for Heat and Mass Transfer, was held 27–31 August at Trogir, Yugoslavia and was devoted to heat transfer from flames. Lectures and short contributions offered information on this subject. The seminar was for the first time preceded by a summer school on the topic: "Heat transfer in fires." Information on the publication of the papers can be obtained from the Secretary General of the Centre, Professor Z. Zaric, P.O. Box 522, 11001 Beograd, Yugoslavia.

The first Heat Transfer Conference in Romania was held at Iasi, 18–20 October 1973. It attracted a large number of scientists from many countries. Seventy papers in three sections discussed measurement techniques and conduction, convection with change of phase and two-phase flow, and applications. Proceedings of the conference are available through the Polytechnic Institute, Iasi, Romania.

The 94th Winter Annual Meeting of the American Society of Mechanical Engineers was held 11–15 November 1973 at Detroit, Michigan. Eleven sessions of the meeting were devoted to heat transfer, including areas like cooling towers, heat transfer in earth materials, and heat pipes. Panel discussions provided an opportunity for exchange of information on heat transfer in food processing, research and applications, environmental and safety considerations in heat-transfer equipment, and fusion reactors. Proceedings of the papers are available through the Society and many of them will also be published in the *Journal of Heat Transfer*.

The 66th Annual Meeting of the American Institute of Chemical Engineers, held in Philadelphia 11–15 November 1973 contained in its program a number of papers on various heat-transfer topics. These, as well as papers at other A.I.Ch.E. meetings, are published in special issues of the *A.I.Ch.E. Symposium Series*. Volume 69, No. 131, deals with "Heat transfer fundamentals and industrial applications". An International Meeting on Reactor Heat Transfer was held at Karlsruhe 9–11 October 1973 and discussed subjects like turbulence, one- and two-phase flows, critical heat flux, and heat-transfer problems related to reactor safety. Proceedings have been published by the Gesellschaft für Kernforschung mbH. Karlsruhe 1973.

Two meetings dealt with processes in which heat transfer plays an important role. The International Congress—"The Sun in the Service of Mankind", held in Paris 2–6 July 1973 assembled a large number of participants from all areas of the globe. The Twenty-Sixth Annual "Gaseous Electronics Conference" held 16–19 October 1973 at Madison, Wisconsin included papers on transfer processes in ionized gases and in arcs, as well as thermal and radiative properties of plasmas.

Developments in heat-transfer research during 1973 can be characterized by the following highlights: phase change, moving boundaries, numerical methods, and fins found special attention in the study of heat conduction. Research in channel flow covered the influence of variable properties, non-Newtonian fluids, and heat-transfer augmentation. Unsteady conditions and chemcal processes were included in boundary layer studies and experiments concentrated on turbulent flow. Various models describing turbulent transfer were investigated and compared. Change of phase and two-phase flow still find considerable attention. Radiative transport in gray and non-gray media continues to attract great interest. In addition, there is a substantial number of papers devoted to problems involving simultaneous conduction and/or convection with radiation. Radiation properties at high temperatures were measured for a number of materials. A moderate effort was devoted to liquid metals with heat transfer in boiling and in condensation. Applications of heat-transfer processes dealing with energy production, space shuttle, and heat pipes have been reported in many journals. Heat-transfer studies in plasmas reported during the past year refer to fundamental investigations as well as to applications, especially to those associated with electric arcs. Equilibrium properties of various substances were measured in the supercritical state and transport properties were investigated for porous metallic materials, for alloys, and for porous wicks.

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 the category.

CONDUCTION

Publication activity in the field of heat conduction appears to be on the rise. A major focus has been on problems involving phase change. A number of papers dealt with numerical methods, both with respect to the principles of their application as well as with results for specific problems. Fins have also evoked some publication activity.

In the phase-change area, a series of papers dealt with various facets of perturbation solution methods. In [60A], a perturbation method which uses the freezing front position as an independent variable (replacing time) provided solutions for outward and partial inward spherical solidification of a liquid initially at the freezing temperature; the method has been extended to the case where the thermal properties of the solidified material vary with temperature [61A]. When the freezing front approaches the center of the sphere, a perturbation solution obtained from the method of strained coordinates can be employed [62A]. A perturbation method, augmented by numerical computation, was successfully applied to solve the planar solidification problem where there is convection heat transfer at the exposed surface [63A]. A variety of other solution methods were also considered. Huber's method for handling one-dimensional phase-change problems has been proven to be convergent and error estimates were given [22A]. The representation of the latent heat effect by a large heat capacity over a small temperature range was used as a basis for a three-time-level implicit numerical scheme for solving phase change problems [11A]. An approximate method for calculating freezing in the region outside of spheres or cylinders was based on the postulate that the region of influence of the cold surface bears a constant ratio to the radius of freezing [28A]. Application of finite integral transform techniques to moving boundary problems (e.g. phase change) gives rise to a system of ordinary differential equations which may be integrated numerically; the method was used for plane, cylindrical, or spherical moving boundaries [73A, 74A].

The solution for freezing and melting fronts, which move out in opposite directions from the interface between a pair of semi-infinite solids, was applied to a molten nuclear fuel (UO_2) and its stainless steel cladding [21A]. For a porous medium containing zones of liquid and vapor separated by an evaporation front, the relationship between the temperature and heat flux at the surface of the medium was found to be multivalued [72A]. Heat balance integral solutions for phase change in a semi-infinite solid took account of variable properties, and suggested that variable and constant property results could be correlated if the properties in the latter were evaluated at the fusion temperature [32A]. A study of transient solidification of a semi-transparent medium by conduction and radiation revealed that the solidification rate is bounded between that for a nonabsorbing medium and that for an opaque medium [29A]. During the solidification process for a non-eutectic alloy, there is a region of pure liquid, a region of pure solid, and a two-phase region that is both liquid and solid [50A]. The film of melted ice water situated between a hot plate and a melting ice surface carries away some of the heat that might otherwise be used in the melting process [42A]. The accounting of the finite heat capacity of an object diminishes the predicted thickness of the coating in the fluidized-bed coating process [1A]. The melting of an iceberg in sea water was analyzed by employing an integral method for the coupled momentum, thermal, and mass diffusion boundary layers [26A]. An analytical solution has been obtained for melting or freezing in a wedge-shaped region, the bounding surfaces of which are maintained at uniform, but not necessarily equal, temperatures [12A].

Formulations and extensions of various numerical solution methods have been described. The finite-element technique was extended to take account of temperature-dependent thermal conductivity in transient heat conduction problems [2A]. Consideration has been given to two ways of treating the variational integral which leads to the difference equations of the finite-element method [71A]. The use of finite-element methods in problems with nonlinear boundary conditions was illustrated by application to the transient temperature distribution in a plane slab which experiences surface heat transfer by convection and radiation [7A]. Difference equations for transient conduction were formulated by the finite-element, finite-difference, and weighted-residual methods; stability and oscillation characteristics were derived and compared [79A]. A technique for dealing with point heat sources or discontinuous boundary conditions can readily be incorporated into existing finite-difference or finite-element solution methods [20A]. Stability, accuracy, and applicability of explicit difference equations for transient conduction problems with temperature-dependent thermal properties were examined; predictions of numerical solutions compared satisfactorily with experiment [34A]. In a follow-on paper, particular emphasis was given to the representation of boundary conditions [35A]. By relating the increments to the thickness of the diffusion layer, a criterion was proposed which provides an *a priori* means of choosing increments for achieving accurate finite-difference solutions to parabolic partial differential equations [17A]. An attractive feature of a three-time-level implicit solution method for transient, variable property conduction is that the properties are evaluated at the intermediate time level, thereby avoiding the need to solve a set of nonlinear equations at each time step [10A]. A variety of solution methods, including various numerical schemes, was advocated and illustrated in order to ensure the accuracy of results for transient diffusion problems involving temperature-dependent properties [48A].

Fins (i.e. extended surfaces) continue to be of interest. The errors that are made by using a one-dimensional fin analysis are shown to depend both on the length–thickness ratio and on the Biot number [41A]. Relatively simple analytical solutions have been constructed to describe two-dimensional temperature fields in fins [70A]. The standard one-dimensional fin solution can be extended to accommodate a spatially varying ambient temperature by appending an additional term [65A]. A quasi-linearization technique was employed to analyze rectangular and triangular fins having nonlinear (e.g. radiative–convective) boundary conditions [18A]. A mathematically rigorous treatment for determining optimum fin shapes has been developed [8A]. The calculus of variations was employed to find the optimum shapes of one-dimensional fins with internal heat generation [3A]. Four methods of determining optimal fin design in the presence of stochastic variations in fin dimensions were applied and compared [45A].

Steady-state problems were analyzed by a variety of methods. The application of conformal mapping enables an exact solution of the steady conduction problem for an infinite plate with a rectangular hole [57A]. A Naylor transform was employed to determine the axisymmetric steady-state temperature distribution in finite spherical cones corresponding to a variety of boundary conditions [59A]. Finite-difference solutions yielded steady-state conductive shape factors for solids contained between a circle and a rectangle [27A]. A least-squares method was employed to fit a steady-state separation of variables solution to a rectangular solid which has a discontinuity in the boundary condition along one side [36A]. As a result of a demonstrated analogy, a heat-conduction analysis for a non-porous region can be employed to design a cooled porous region so as to maintain a uniform surface temperature in the presence of a specified heat flux [75A]. Constriction resistances at the contacts between hollow microspheres were deduced from solutions of Laplace's equation and applied to predict the performance of insulation layers [14A].

A number of methods for solving transient problems was published. The solution of nonlinear transient heat-conduction problems (i.e. variable properties or boundary conditions) can be approximated by solutions of corresponding linear problems that are selected so as to minimize the errors [78A]. A new finite integral transform and the corresponding inversion formula were developed for the solution of diffusion equations in a finite region of arbitrary geometry and initial conditions [49A]. Fundamental Green's functions can be used to transform the differential equations for transient conduction in anisotropic media into integral equations that are easier to solve [15A]. Simultaneous transient diffusive transfer of heat and mass in a cylindrical region has been formulated in terms of integral equations and solutions obtained for small values of time [76A]. Two different ways are demonstrated for constructing the variational principle for transient heat conduction [80A]. The accuracy of using a prescribed temperature condition at an extrapolated boundary to replace a convective condition at the actual boundary is examined for transient conduction in a plane wall, a cylinder, and a sphere [66A]. The accuracy of transient heat-conduction solutions derived by application of convolution integrals and of the method of images is assessed by comparison with exact solutions and with other approximate solutions [9A]. Accuracy estimates for heat balance integral solutions for the transient response of a semi-infinite solid were obtained by comparisons with the exact error function solution [40A].

Solutions to a variety of transient problems have been obtained. Finite-difference solutions provided the basis for temperature–time charts for a plane slab with uniform internal heat sources and radiative boundary conditions [16A]. The impingement of an electric arc on a plate electrode gives rise to transient heat conduction in the plate owing both to surface heating and internal Joule heating of the plate [19A]. When a charged particle interacts with a material, its kinetic energy is converted into thermal energy in a very short distance, resulting in a local increase in temperature whose effects have been analyzed by the thermal spike model [33A]. Point-matching techniques were successfully employed to obtain transient and steady-state results for cylindrical heat sources (i.e. heaters) embedded in a plane slab [68A]. Successive Fourier and Laplace transforms were employed to solve for the transient temperature distribution in a semi-infinite solid having anisotropic thermal conductivity [58A]. An unconventional Hankel transformation enabled the solution of the transient and steady temperature fields in a slab pierced by a cylindrical hole [47A]. Oblate spheroidal coordinates were used to advantage in solving for the transient heat flow in a half-space due to an isothermal disk on the surface [37A]. The thermal mode structure of the temperature field in a laminated composite, in which the layers are lined up parallel to the heat propagation direction, has been determined [30A]. Circumferentially varying and time-dependent surface heat flux distributions can be accommodated by a solution for a laminated composite cylinder [43A]. The effect of a thermal contact resistance between two periodically contacting surfaces depends on the ratio of the contact time to the period of the contact cycle [31A]. The periodic-steady solution for the temperature field resulting from the periodic contact and separation of two surfaces was solved by a semi-numerical procedure [67A]. A variety of thermal wave shapes is possible within forced-cooled superconducting devices [6A].

Papers have been published on the inverse problem of transient heat conduction and on non-Fourier heat flux representations. The internal and surface temperature–time results for a composite solid can be predicted from temperature information given at two interior locations or from temperature and heat flux information given at one interior location [51A]. A method for determining the transient heat flux across a solid interface from temperature–time data is based on the application of Duhamel's integral to a third-order natural splined fit of the discrete data [5A]. Questions of uniqueness have been examined for the inverse problem of transient heat conduction [13A] and for transients characterized by finite wave speeds [56A]. Unlike the conventional Fourier model for heat conduction, the relaxation model predicts an instantaneous jump in the surface temperature when a solid is subjected to a step change in surface heat flux [46A]. A uniqueness theorem has been stated for heat conducting materials with memory [52A].

A pair of papers dealt with property determinations. The concept of controllable heat flux fields was applied to determine temperature-dependent thermal conductivities [64A]. Results for the transient temperature distribution owing to a line heat source in an infinite medium with temperature-dependent conductivity are described as being useful in connection with the measurement of thermal conductivities of liquids [69A].

English-language translations of Russian papers dealing with the following heat-conduction topics have appeared in *Heat Transfer/Soviet Research*: (a) inverse problem of transient heat conduction [4A, 44A]; (b) integral methods [25A]; (c) phase change and moving boundaries [54A]; (d) temperature-dependent properties [38A]; (e) internal heat generation [39A]; (f) laminated shells [23A]; (g) difference equations [53A]; (h) property determinations [77A]; (i) instrumentation [24A]; and contact resistance [55A].

CHANNEL FLOW

Papers dealing with heat transfer in ducts covered a broad range of topics, with particular interest in the areas of variable property effects and non-Newtonian flows.

Experimental data for turbulent air flow in an annulus with large wall-to-bulk temperature differences and significant property variations correlated well with similar data for circular tubes [18B]. The effect of cooling on turbulent heat transfer for air in a pipe was correlated by the factor $(T_s/T_B)^{-0.17}$, where T_s is the surface temperature and T_B is the bulk temperature [71B]. Numerical solutions for laminar gas flows in tubes with various degrees of wall cooling showed the wall friction and pressure variation to be sensitive to the intensity of the cooling, but the average heat-transfer coefficient was less sensitive [4B]. Analytically determined velocity profiles for fully developed laminar flow in a rectangular duct evidenced considerable distortion when account was taken of temperature-dependent viscosity [10B]. Experiments on non-isothermal laminar flow in vertical tubes indicated that the common analytical assumption of constant viscosity is justifiable only for mild non-isothermal conditions [6B]. Variable property solutions for laminar gas flows in the entrance region of a porous-walled parallel plate channel provided criteria for delineating the range of applicability of the constant property solutions [19B]. The experimental results for heated laminarizing gas flow in square ducts indicate that the usual acceleration parameter is not a good indicator of incipient laminarization and that a wall shear stress parameter is more effective [49B].

Numerical solutions for laminar non-Newtonian pipe flows show that the effect of a temperature-dependent consistency index on heat transfer is less marked for the uniform flux boundary condition than for the uniform wall temperature boundary condition [20B]. The temperature dependence of the consistency index of pseudo-plastic fluids may influence the heat transfer in a channel flow more than the non-Newtonian character itself [37B]; a similar finding applies for pipe flow [36B]. For low Reynolds number, non-Newtonian laminar flow through a sharp inlet into a tube, numerical solutions revealed distortions of the inlet-section velocity profiles, both for isothermal and non-isothermal conditions [17B]. Fully developed steady flows of non-Newtonian fluids with viscous dissipation can exhibit double-valued solutions; that is, for a given pressure gradient, there may exist two entirely different temperature profiles [64B]. For thermally developed conditions, the effect of viscous dissipation was evaluated for laminar non-Newtonian flow in ducts [47B]. The use of the differential viscosity led to a successful correlation of turbulent pressure drop and heat transfer data for non-Newtonian tube flow [43B]. Measurements have confirmed the hypothesis that the change in heat-transfer coefficient which occurs with the addition of polymers to a turbulent pipe flow is due to extinction of high-frequency turbulent pulsations [48B]. Continuous injection of a concentrated polymer solution into a turbulent pipe flow produces long polymer threads which cause similar reductions in drag and heat transfer [66B].

Augmentation, roughness, and inlet disturbances have been investigated. The use of spiral and helical turbulators in turbulent flows can result in significant decreases in the tube surface area required to accommodate a given heat load [32B]. Blade-induced swirl in turbulent pipe flow of water increased the heat-transfer coefficients by as much as 40 per cent for the same pumping power [58B]. Analysis showed that impressive augmentation of the heat-transfer coefficient can be attained by the use of internal fins in laminar pipe flows [25B]. Electrochemical mass transfer was employed to study the effect of two-dimensional roughness on the transfer coefficients in a rectangular duct. The increase in the transfer coefficient was attributed to changes of the mean velocity and temperature distributions due to intense turbulence near the wall [44B]. Experiments with turbulent airflow in an internally heated annulus indicated that the shape of the upstream unheated section has a significant influence only in the first one or two equivalent diameters of the heated section [59B].

Several papers have dealt with turbulent exchange processes. Measurements of spectral correlations in turbulent airflow in a tube show that heat and momentum are transferred identically in the energy-containing range of wave numbers in the wall region, but that in the core the heat-transfer process is more effective [7B]. Tracer techniques were employed to measure eddy diffusivities in rod bundles under cross flow conditions; the measurements yielded a turbulent Peclet number which varied with the $-0{\cdot}71$ power of the Reynolds number [23B]. Pipe flow mass-transfer experiments involving brine in water showed that the Schmidt number was not a significant factor in effecting the ratio of the eddy diffusivities of mass and momentum [53B]. Available information on the eddy diffusivity for tangential heat transport in tubes has been brought together; in general, the tangential diffusivity is substantially greater than the radial diffusivity near the tube wall [27B]. A model has been proposed to explain the dynamics of the axial heat transfer in turbulent flow in a tube [57B].

Supercritical and compressible flows have been studied. High frequency oscillations present in supercritical water flowing turbulently in a uniformly heated tube were shown to be associated with pressure oscillations in the test section resulting from a standing pressure wave between entry and exit [60B]. Marked circumferential variations of the local heat-transfer coefficient were in evidence in a rectangular duct with turbulent flow of supercritical CO_2; only one wall of the duct was heated [52B]. By accounting for the enhancement of the eddy diffusivity by the density variation, calculated heat-transfer coefficients for supercritical water in a heated tube were found to agree fairly well with experimental data [69B]. An analysis of compressible, dissipative flow in a tube reveals marked differences in the temperature profiles for laminar and turbulent conditions [51B].

Non-circular ducts continue to be of interest. Experiments on longitudinal turbulent flow in a square-array rod bundle provided an upper limit representation for the Nusselt number [40B]. The heat-transfer performance of various arrangements of the rods in a bundle was examined [41B]. Corner effects on turbulent heat transfer were found to be different in the entrance and developed regions of a rectangular duct [24B]. The turbulent heat-transfer coefficient for airflow in a converging rectangular duct is higher than that for a straight duct [68B]. At lower turbulent Reynolds numbers, reduced heat-transfer coefficients were found to prevail in elliptical ducts having larger aspect ratios; the reduction was believed due to localized regions of laminar or transitional flow [11B]. A Graetz-type analysis for laminar slug flow in elliptical ducts indicated that for small aspect ratios (ratio of minor to major axis), the Nusselt numbers decrease with decreasing aspect ratio [21B].

Surface mass-transfer effects and phase change were considered. A Couette-flow model for viscous heating in a porous bearing demonstrated that substantial reductions in temperature can be achieved by the injection of a high Prandtl number lubricant [67B]. Experiments with turbulent airflow in a heated porous tube revealed a substantial increase in the Nusselt number due to suction [1B]. Similarity solutions exist for fully developed laminar flow in a porous-walled paraboloidal duct with injection as well as for round pipes and parallel-plate channels [30B]. Measurements of evaporative mass transfer from one wall of a rectangular duct to a turbulent airflow agreed reasonably well with analytical predictions, with deviations being attributed to uncertainties in the turbulent Schmidt number [38B]. In an investigation of freezing of a liquid flowing turbulently in a cooled tube, it was demonstrated that supercooling of the liquid may occur [3B]. A finite difference calculation for determining the point of ice formation for laminar liquid flow in a cold-walled tube revealed inaccuracies in a previous Graetz-type solution [26B].

There appears to be a heightened interest in transient processes. An exact solution of the conjugate thermal transient in a laminar slug flow and its bounding wall enabled the assessment of the applicability of a quasi-steady model [61B]. Results for the transient initiated by step-change heating of the walls of a laminar channel flow provided information on the duration of the transient period [42B]. The downstream decay of a time-varying temperature at the entrance section of a duct was found to depend upon the frequency of the temperature variation and upon the Reynolds number [28B]. An extension of the laminar Graetz problem to include a thermal transient also takes account of axial conduction [45B]. An integral equation has been derived (but not solved) to describe the transient temperature field in a slug flow and in its bounding tube; the transient is caused by an abrupt temperature change at the entrance cross section [70B].

Laminar flow analyses dealt with a variety of topics. The thermal entrance length for laminar flow in a channel with wavy walls is very little different from that for a straight-walled channel [15B]. For analyzing the effects of axial conduction in the Graetz problem, it was found convenient to transform the axial coordinate so that the axial extent of the problem is finite rather than infinite; finite difference techniques were readily applied to the transformed finite-length pipe [65B]. An analysis for laminar slug flow in a parallel-plate channel revealed the importance of upstream and downstream thermal boundary conditions when the Peclet number is low, thereby underscoring the influence of axial conduction [62B]. The accounting of the Joule–Thomson effect in the laminar Graetz problem gives rise to an axial Nusselt number distribution which reaches a local minimum in the thermal entrance region [13B]. The efficiency of a multi-channel laminar heat exchanger consisting of a stack of parallel-plate channels in counterflow was determined by solving a set of linear integral equations that express the interactions between the channels [5B]. Fully developed Nusselt numbers and entrance lengths are given for a parallel-plate heat exchanger with laminar flow on one side and turbulent flow on the other [56B]. A variational method has been formulated and applied to laminar forced convection heat transfer in ducts [34B].

Available analytical and experimental information for laminar tube flow with uniform wall heat flux has been correlated for all Prandtl numbers [16B]. A comprehensive tabulation lists available laminar thermal entrance region solutions for tubes, channels, and rectangular ducts [33B]. The thermal entrance length for either laminar or turbulent duct flows having uniform wall heat flux can be estimated from a knowledge of the fully developed temperature profile [55B].

Experiments with steam flowing turbulently in a heated tube suggest that the Nusselt number is somewhat increased by the effect of radiation [14B]. Laminar flow experiments with glycerol in a heated circular tube yielded velocity profiles, pressure distributions, and heat-transfer coefficients in good agreement with finite difference solutions [35B]. A jet of gas, directed into one end of a tube that is closed at the other end, produced strong oscillations within the tube; the dissipated mechanical energy gave rise to significant temperature increases in the gas and at the tube wall [8B]. The end result of an analysis of turbulent pipe-flow heat transfer to gases with suspended solid particles is a Nusselt number expression which can be evaluated when pressure drop data is available as input [22B].

English-language translations of Russian papers dealing with the following heat-transfer topics have appeared in *Heat Transfer/Soviet Research*: (a) variable property effects in gas flows [2B, 50B, 63B]; (b) turbulent flows with polymer additives [12B, 31B] and laminar flow in polymer melts [54B]; (c) heat transfer in a swirl chamber [9B]; (d) unsteady turbulent heat transfer in tubes [29B]; (e) flow in an annular duct at supercritical pressure [46B]; (f) flow in triangular ducts [39B].

BOUNDARY LAYER AND EXTERNAL FLOWS

The laminar boundary-layer equations are well established and have, during the past year, again been used to study various situations. An analysis [10C] established and used the analogy between the effect of a velocity variation along a streamlined surface on the friction factor and the temperature variation along the surface on the heat transfer for a fluid with a Prandtl number approaching zero. The effect of heat conduction within the wall on laminar film heat transfer was studied [27C, 28C] resulting in good agreement with experiments. Correlation equations [5C] describe laminar forced convection in flow over an isothermal flat plate or entering an isothermal tube. Local heat transfer around a cylinder [22C] at Reynolds numbers between 74 and 4640 and on an isothermal sphere [9C] at Reynolds numbers between 0·1 and 20 was analyzed and measured for a fluid with a Prandtl number near 1. Empirical equations are presented [29C] for the calculation of heat transfer to yawed cylinders.

Several papers are concerned with unsteady conditions. Heat transfer in an unsteady laminar boundary layer on a surface moving with a time-wise varying velocity into a stagnant fluid was calculated [11C] and heat transfer on a plate oscillating with frequencies from 1 to 60 Hz was measured [12C]. Unsteady heat transfer in a two-dimensional laminar wall jet of fluids with Prandtl numbers between 0·01 and 1000 flowing over a surface with a step increase in temperature at time zero was investigated [16C]. The time-mean heat-transfer coefficient in a periodic laminar boundary layer near a two-dimensional stagnation point decreases at low frequency but increases slightly at high frequency [18C]. An analysis [31C] of the effect of periodic crossflow on the heat transfer of a laminar axisymmetric boundary layer compares well with experiments on a cone-cylinder in supersonic and hypersonic flow. Heat transfer from a vibrating circular cylinder in a fluid at rest was analyzed [8C] based on the acoustic streaming flow field for small and large Reynolds numbers. A calculation established laminar heat transfer of a non-Newtonian powerlaw fluid in flow past a wedge with a local step discontinuity of the surface temperature [2C].

The introduction of vortices with axes parallel to the flow direction results in large increases of the heat-transfer coefficient in stagnation flow for large Prandtl number and non-Newtonian fluids [14C].

Experiments have been performed to establish the characteristics of turbulent boundary layers. Results of such studies were reported for a strongly accelerated turbulent boundary layer [20C], including transpiration in the form of local heat-transfer coefficients and of turbulent intensity profiles. A hypersonic gun tunnel was used to study heat transfer in a turbulent boundary layer on a flat plate [6C] and at a wedge corner [7C]. Stanton numbers were predicted for a turbulent boundary layer with pressure gradient [15] based on mixing theory and on a surface renewal model [32C]. Integral methods were described using friction factor and Nusselt number as variables [3C, 30C] and were found to agree well with experiments. The effect of viscous dissipation on turbulent forced convection heat transfer was analyzed [4C].

An approximate calculation considered heat transfer from a cooling pond to the atmosphere [26C] modeling this process as turbulent boundary-layer flow over a rough surface. Heat transfer on a surface with roughness elements is described [23C] by a correction factor depending on the ratio of total surface to plane surface area and applied to the Nusselt number for flow over a plane surface.

A recalculation of Hilpert's constants using new experimental evidence results in tabulated values for A and n in the relationship

$$Nu_f(T_f/T_\infty)^{-0\cdot17} = ARe_f^n$$

[13C]. The Nusselt number is also described by the relation

$$Nu_f(T_f/T_\infty)^{-0\cdot17} = 0\cdot184+0\cdot324Re_f^{0\cdot5}+0\cdot291Re_f^x$$

with

$$x = 0\cdot247+0\cdot0407Re_f^{0\cdot168}$$

for Reynolds numbers between 0·01 and 10^5. Heat transfer in a laminar and turbulent steady and unsteady liquid film on a vertical wall was analyzed [17C, 25C]. Experiments and analysis also established heat-transfer values to a vertical cylindrical laminar liquid jet ejected into a stagnant gas [19C]. As expected, the main resistance to heat transfer was found to be concentrated in the gas.

A theoretical investigation of a laminar boundary layer with combustion on a flat plate using Arrhenius' equation for the chemical kinetics [21C] resulted in temperatures lower by several hundred degrees than values found previously. Numerical calculations solved the conservation equations and relaxation equations describing laminar flow with vibrational non-equilibrium [33C] for flow behind a shock in a shock tube and along a non-catalytic flat plate. Coles' parameter representation was used to develop an integral technique [24C] for non-equilibrium compressible boundary layers. The effect of surface catalytic activity on stagnation heat transfer was studied experimentally in an arc facility [1C]. Heat transfer to a silicon dioxide surface was found to be only one-third of the value on a nickel or platinum surface.

FLOW WITH SEPARATED REGIONS

The yearly published literature on separated flow heat transfer has been decreasing. The transition from highly analytical works to practical applications does not appear to be taking place.

Single bodies

An exact solution to the energy equation is given [6D] for a near-separating laminar boundary layer with continuously zero wall shear stress. The effects of foreign gas mass injection on the interaction region just below "blowoff" separation is described [1D]. Kalra and Uhlherr describe experiments [12D] on mass transfer between the attached recirculating wake of a sphere and a circular disk set normal to the flow. A numerical scheme of integration is devised [23D] to integrate the unsteady laminar boundary-layer equations with partly reversed flows.

Three flow regimes are observed [2D] in the flow field downstream of an abrupt expansion in a circular channel. Turbulent separation zones are examined [21D] for flow around steps in the form of cylinders and rectangular parallelipipeds with square bases. Detailed measurements of turbulence quantities in the interacting wake of two cylinders are given [5D]. The primary conclusion is that surprisingly simple formulations can be used in predicting the dominant features. Surface-to-freestream temperature ratios greater than unity destabilize the boundary layers on subsonic airfoils, hastening transition and separation along with a significant reduction in stall angle with T_w/T_∞ [17D]. Convection, production, diffusion, and dissipation of temperature fluctuations have been measured in a turbulent wake behind an optically heated sphere [7D].

Laminar separation in a uniform shear flow is examined [13D, 14D]. Gray and Rhudy describe [9D] effects of blunting and cooling on laminar supersonic separation. Reference [4D] examines experimentally the geometric parameters which influence the extent of heat transfer in non-axially symmetric regions for an inclined cylinder in supersonic flow. A numerical study is made of the nature of the supersonic separating boundary layer [26D] with the result that all non-reacting flows are singular at separation. Smith and Stewartson [20D] analyze fluid injection into a separated supersonic boundary layer created by strong (but less than massive) injection.

Detailed measurements at $M_\infty = 2\cdot6$ over a compression corner using hot wire probes [18D] are welcome. Reference [25D] gives experimental heat flux values behind a rearward facing step at $M_\infty = 10$. Heat transfer in the reattachment region [16D] and downstream of reattachment [8D] continue to receive attention. The method of integral relations is applied to calculate pressure and velocity profiles in supersonic laminar wakes [10D].

Packed and fluidized beds

Tube banks positioned longitudinally in fluidized beds have a greater thermal retarding capacity than with transverse orientation [3D]. Turner and Otten give values of thermal parameters in packed beds [24D]. A new model [15D] for heat transfer between solid particles and gas in a fluidized bed has been proposed on the basis of the bottom bed properties. In injecting solutions and melts into a fluidized bed by pneumatic or pneumo-mechanical injectors, a region free of particles—a gas jet, is formed in the bed where the liquid stream breaks up into droplets as if to form a spray zone [19D]. The introduction of suspended particles into an ascending stream of liquid drops (a liquid fluidized bed) significantly increases the heat transfer [22D]. Experimental data for particle-to-fluid heat transfer is fixed and fluidized beds of small particles at low Reynolds numbers display abnormally low Nusselt numbers when total particle surface is taken as the heat-transfer area [11D]. Werther describes data in gas–solid spouting fluidized layers [27D]. Zabrodsky also deals with compound heat exchange between a high temperature gas-fluidized bed and a solid surface [28D].

TRANSFER MECHANISMS

The influence of total temperature on transition in supersonic flow predicted by stability analysis was not verified experimentally [11E] and Hanks' stability criterion failed to predict transition for two-phase flow [2E]. An extension of Van Driest's damping parameter describes the effect of mass transfer in agreement with experiments [3E]. An effective viscosity model [1E] for turbulent wall boundary layers includes the effects of a pressure gradient, of wall roughness and of transpiration. None of the proposed expressions for Prandtl's mixing length gives results as good as methods using differential equations to describe turbulence parameters [7E], but they lead generally faster to results. It is argued on the basis of numerical computations of low Reynolds number flows [5E] that only procedures which introduce differential equations for the turbulent energy and the dissipation rate describe conditions satisfactorily as they are found in thermal power equipment. Experiments determined the ratio of Reynolds shear stress to turbulence kinetic theory [10E] in compressible boundary layers near equilibrium flow and established also thermal and momentum diffusivities for flow of warm water over a cold water pool as a function of Richardson number [9E]. The local turbulent Prandtl number was found [2E] to depend on the fluid Prandtl number near a wall but not away from the wall. A value 0·885 was found experimentally for the mean turbulent Prandtl number in flow of water over a smooth wall [4E].

Temperature differences decay faster in supersonic grid turbulence [8E] than was previously reported. The lateral component of freestream turbulence in a contracting flow was found to decay in a similar way as in isotropic turbulence [6E], whereas the longitudinal component decayed in an entirely different manner. A study of the decay of turbulence in a closed vessel [13E] indicated that the decay was in the later period not influenced by the way in which the turbulence was generated but only by the walls of the vessel.

NATURAL CONVECTION

Interest in natural convection continues at a high level. Such flows are of interest to the applied mathematician, the engineering scientist, the academician (both senior and junior) interested in developing methods for predicting stability and analyzing and testing turbulence models, and to the applied engineers through applications such as solar energy collectors and combined free and forced convection.

A simplified correlation for laminar natural convection from a vertical flat plate has been presented for different thermal boundary conditions and for fluids of various Prandtl number [18F]. Another approximation specifically looks at the heat transfer from a vertical plate to a high Prandtl number fluid [76F]. A simple analysis is used to explain the similarity of the heat-transfer correlations from different submerged bodies [53F].

An integral approach is used to analyze natural convection on a vertical plate in water held at a temperature in the neighborhood of its maximum density [79F]. Analyses have been presented for the natural convection from a vertical plate to a non-Newtonian fluid including a Sutterby fluid [25F] and a power law fluid [14F]. An analysis of the flow past a heated vertical plate examines the different transient regimes [11F]. Thermal coupling through a wall separating two fluids at different temperatures has been idealized to obtain the natural convection boundary layers on each side [54F].

An analysis of natural convection on a porous vertical plate includes some variable property effects [19F]. An analysis of the laminar boundary layers on two vertical flat plates at right angles confirms the experimentally observed chimney effect in the corner region in which the vertical velocity is larger than that on a single heated vertical plate [74F]. A correlation is presented for the heat transfer from vertical U-shaped channels as might apply in a vertical fin array [83F].

A calculation of natural convection flow around a horizontal cylinder shows the significance of viscous forces in different regions near the bottom of the cylinder [73F]. The effect of a sound field on the heat transfer from a horizontal circular cylinder has been examined [22F]. Heat transfer near the bottom of a cylinder due to heat sources within the surrounding fluid has been examined [1F]. Different subliming solids have been used to measure natural convection from horizontal circular cylinders, flat plates, and spheres [71F]. Measurements have been made [65F] of the natural convective heat transfer from horizontal cones. An experiment and analysis are used to determine the local Nusselt number from natural convection through a vertical tube bundle [21F].

Heat transfer by natural convection to a fluid near its critical point has been examined in two studies. One study [7F] finds no boiling-like phenomena above the critical point. In the other study [64F] the heat transfer from wires of different materials to carbon dioxide in the super-critical region is studied.

A mass-transfer analogy was used to study heat transfer from a heated isothermal plate facing upwards [30F]. Natural convection has also been studied from a cooled plate facing downward [80F] and from parallel heating strips on a horizontal surface [8F].

The boundary layer near the edge of a horizontal or slightly inclined heated surface has been examined [69F]. A companion work examines the stability of such flows [68F]. Another study analyzes the free convection from a semi-infinite flat plate inclined to the horizontal [49F]. Studies of the instability on inclined surfaces shows the prevalence of longitudinal vortices [36F] and the importance of lateral flows [35F]. The rate of dissolution of a solid in a liquid is measured to determine the mass-transfer rate from a horizontal surface with the final shape of the surface giving an indication of the flow profile [43F].

A careful study of the buoyant plume above a horizontal line heat source finds swaying of the plume [26F]. Indirect measurements were made [23F] to determine the mass rate of flow in the plume above a horizontal cylinder. An analysis of the stability of buoyant plumes includes the effect of non-parallelism of the flow [34F]. Experiments on the wake above an isothermal vertical plate agree well with analysis [37F]. Buoyancy in a round vertical laminar jet primarily affects the axial velocity component [58F].

Free convective flows in enclosed systems are examined in a variety of works. A number of these continue to concentrate on the general problem of heat transfer in horizontal fluid layers. A two-dimensional analysis of such a flow with upper and lower free surfaces has been extended to Rayleigh numbers fifty times the critical value [59F]. A study of the transition to turbulent flow in horizontal fluid layers has examined the effects of fluid Prandtl number [51F]. Critical Rayleigh numbers are calculated [81F] in a conducting fluid layer in the presence of a magnetic field. At high Rayleigh numbers in turbulent flow, optical measurements [28F] determine the vertical velocity component of the fluid. An interferometric study [17F] indicates the possible occurrence of reversal of the mean vertical temperature gradient at moderate Rayleigh numbers.

Introduction of a honeycomb into a horizontal fluid layer heated from below inhibits the heat transfer [41F]. The effect of rotation on low Rayleigh number convection is examined numerically [78F]. A non-linear analysis predicts the heat transfer in a rotating annulus heated from below [29F]. The flow pattern and heat transfer following the transient heating of a horizontal fluid layer have been examined [63F]. Another study [16F] introduces problems of unsteady free convection in enclosed volumes.

An alternating electric current in a dialectric fluid is used to establish the body force in studying thermal convection [13F]. Thermal convection including radiation effects in non-gray fluids has been examined in horizontal layers [2F] and in an asymmetrically heated vertical slot [3F]. Two different studies [48F, 55F] consider exothermic reactions in a fluid and their influence on a convecting flow.

A theoretical study [87F] indicates that the presence of longitudinal or transverse rolls in thermal convection between non-uniformly heated plates depends on the fluid Prandtl number. The heat transfer in vertical cells of rectangular cross-section has been measured in laminar and turbulent regimes [46F].

The motion of a turbulent buoyant thermal in a stably stratified atmosphere has been described [85F]. The effect of temperature stratification on laminar free convection has been examined [31F]. Density inversion effects the stability of the natural convection in a horizontal layer of saline solution [83F]. Different types of disturbances are considered in examining the stability of a natural convection boundary layer in a stably stratified medium [45F].

Several works examine natural convection in porous media. In one [33F] a theoretical bounding curve for the heat transport through such a layer is calculated numerically. Different types of periodic flow are observed in thermal convection in an inclined porous layer [9F]. Combined natural and free convection in porous media are studied in an approach to the flow in a nuclear reactor [47F].

Study of convection in a liquid layer is applied to problems involving liquid metals covered with "dross" [10F]. In a two-component initially homogeneous system, the Soret effect initiates migration in a horizontal fluid layer across which a temperature difference is applied [70F].

The critical Rayleigh number for an inclined air layer at different angles was measured [42F]. The scaling of the heat-transfer results obtained for horizontal layers to inclined layers has been discussed [20F].

The development of finite amplitude convection in a vertical slot containing a stably stratified fluid has been investigated [38F]. Numerical solutions to natural convection in a vertical parallel plate channel with one insulated face agree well with experimental measurements [56F]. The stability of the conduction regime of natural convection in a vertical slot is strongly dependent on the Prandtl number of the fluid [50F]. Convection of a non-Newtonian fluid in a vertical parallel plate channel has been studied [5F]. Unsteady laminar convection in uniformly heated vertical cylinders has been analyzed [32F]. The heat transfer from a fine wire in a vertical cylinder has been found to be predominantly by conduction except at the extremities of the wire [27F].

A numerical solution for the flow of a fluid in a heated cavity includes non-steady effects [77F]. Convection in a heated cavity has been studied using water near its maximum density point [86F]. Experiments on the flow of an inclined fluid layer with heating on the bottom shows convective rolls superimposed on the basic motion [39F]. The conditions under which boundary-layer solutions apply in a tilted cavity with differentially heated side walls has been determined [4F].

Dimensional analysis arguments are put forward to get relationships for the heat transfer by natural convection in cylindrical and spherical fluid layers [6F]. Studies of natural convection in spherical annuli include observations of a different flow regime [91F]. The heat transfer in such cavities increases when the center sphere is moved upwards or downwards from the concentric position [88F].

Many studies consider the effects of combined natural and forced convection in which a flow is set up by some external means and buoyancy forces can significantly alter the flow and the heat transfer. These include studies concerned with both external flows and flows in ducts. A similarity solution was used for the combined convection on a vertical surface [89F]. A numerical calculation shows the combined convective flow over a flat plate inclined at an angle to the vertical [67F], while an experimental study [66F] shows the effects of opposing flow on heat transfer from a vertical plate. An analysis shows how buoyancy affects a two-dimensional wall jet on a vertical plate [90F], while a similarity solution gives the combined natural and forced convection flow over a thin needle [61F]. Several different analyses consider the combined forced and free convection flow over a horizontal flat plate [40F, 52F, 75F]. The product of Grashof number times Reynolds number squared appears to determine the flow regimes for combined convection from horizontal cylinders to water [24F]. The roughness of bare stranded conductors appears to have little effect on heat transfer from a horizontal wire, while inclination from the horizontal decreases the heat transfer [60F].

The critical Rayleigh number has been determined for convective instability in the thermal entrance region of a horizontal parallel plate channel heated from below [44F]. Under different flow conditions, either velocity or temperature fluctuations can predominate in mixed convection in a horizontal tube [62F]. Other experiments [92F] show the heat transfer by mixed convection in the annulus formed by two coaxial cylinders.

An approximate method [72F] is used to analyze mixed flows and to predict the heat transfer between finite vertical plates. An analysis applicable to turbulent flow considers buoyancy and acceleration in vertical circular tubes [82F]. Detailed measurements [12F] show the effect of buoyancy on low Reynolds number pipe flows. A numerical solution for fully developed mixed laminar flows in inclined tubes has been presented [15F]. Another analysis concerns mixed flow in rotating curved rectangular tubes [57F].

CONVECTION FROM ROTATING SURFACES

Asymptotic solutions [8G] describe the heat transfer in laminar forced flow against a non-isothermal rotating disk for large and small Prandtl numbers. Analysis and experiments determined the heat transfer in evaporation of liquid from a film on a rotating disk [1G] and during condensation of steam on a rotating horizontal disk [2G]. A laminar analysis and turbulent experiment [6G] determined heat transfer for radial flow of a fluid between two disks rotating with equal speeds. Situations existing in gas turbines instigated experiments [10G, 11G] to determine the flow field and local heat-transfer coefficients in cavities of cylindrical shape with length to diameter ratios from 4/9 to 2 with some of the walls rotating and others being stationary and with through flow of air. A contrived transient computer method [3G] offers advantages for the calculation of steady state flows in cavities and for flow situations similar to the ones described in the preceding sentence. Formulas were derived [5G] from experiments which describe the Nusselt number for heat transfer from a rotating sphere to air at rest or flowing past. Convective heat transfer through the annular space between a rotating heated inner sphere to a stationary outer sphere was found [7G] to be smaller than heat transfer to a rotating single sphere for a Reynolds number range from 2 to 10000 and for Grashof numbers from 6×10^6 to 20×10^6. Turbulent friction factors and heat-transfer coefficients were obtained [9G] for swirl flow of water produced by a helical vane in an annulus. They can be predicted by adjustment of the values for straight flow. An optical method was described [4G] for the study of the movement of droplets produced by steam condensation in swirl flow regions of turbine cascades.

COMBINED HEAT AND MASS TRANSFER

Studies of combined heat and mass transfer continue with considerable emphasis in the areas of film cooling and transpiration cooling. Applications of film cooling appear to concentrate on high temperature gas turbines, including the transfer in combustors and on stationary and rotating blades. Although the specific applications for transpiration cooling are not often cited in the literature, there is continued analytical and experimental work in that field.

A correlation for two dimensional film cooling near the injection region has been presented [1H]. The effect of step height on film cooling effectiveness has been measured [10H]. An analysis of multiple slot film cooling with laminar flow shows the importance of slot height with a given injected mass [18H].

On a wall exposed to a supersonic stream, the effect of injection on thickening the boundary layer is used to explain the influence of film cooling on local heat transfer [23H].

Measurements [16H] and calculations [15H] of the film cooling effects downstream of discrete holes, as might be encountered in a combustion chamber, agree remarkably well. Experiments on full coverage film cooling in which a two-dimensional array of injection holes is used correlated quite well using the principle of superposition [11H].

Several Russian studies are concerned with film cooling specifically on the blades within gas turbines. These include the effects of two dimensional injection on turbulent boundary layer heat transfer [25H], the effect of film cooling on airflow past a turbine blade [21H], and temperature measurements on a film cooled blade [24H].

Experiments on film cooling downstream of a row of holes confirm earlier results [19H]. An expression is derived for film cooling effects downstream of a number of slots [17H]. Applicability of an adiabatic wall temperature in film cooling studies has been reconfirmed [22H]. Liquid film cooling using a water layer up to 0·7-mm thickness has also been studied [20H].

Simplified relations are presented for the friction and heat transfer on a porous surface with blowing [7H]. Under certain conditions, blowing through a porous surface can apparently increase the heat transfer from a hot flow to the wall through a laminar boundary layer [4H]. A boundary-layer prediction shows a significant effect on heat-transfer rate due to variable surface temperature with transpiration cooling [14H].

Calculations of transpiration cooling heat transfer near a stagnation point have been made [3H, 5H]. A special calculation technique has been used for studying boundary-layer flows with massive blowing [8H, 9H]. Generalized experimental data on heat transfer over a range of blowing rates and freestream velocities (up to Mach 4) have been obtained [12H].

The heat transfer on a transpiring surface with strong injection has been examined experimentally [2H] and theoretically [13H].

Calculations of transpiration cooling have been extended to an unsteady case [6H].

CHANGE OF PHASE

Boiling

Soskov [87J] determines the limits of incipience of developed subcooled boiling in heat exchanger geometries. Instability and suppression of boiling are particularly well marked in the alkali metals [85J]. Larger boiling heat-transfer coefficients with higher thermal conductivity walls are caused by wall temperature profiles and not microlayer evaporation [49J]. Katto *et al.* give a law for microliquid layer formation [47J]. Temperature fluctuations of the heated surface at an active nucleation site are considered [96J].

A general framework for the effect of bubble motion on the collapse rate has been suggested [65J] for a single bubble of constant and variable rise velocity, including the effect of cross flow, which can be applied to multi-bubble systems. At frequencies up to 20 bubbles per second, the collapse rate of a bubble train is theoretically smaller than that of a single bubble and approaches the latter at high frequencies [66J]. The collapse behavior is well predicted [5J] using laminar heat transfer. An explicit finite difference analysis [38J] predicts that a vapor bubble in sub-cooled water grows in a roughly spherical fashion [95J] but collapses in a highly non-spherical manner.

Kichigin and Povsten [48J] study acoustic phenomena accompanying changes in pool boiling modes. They have the opinion that the critical heat flux should be defined where individual bubbles begin coalescing into unstable vapor films irrespective of the kind of temperature jump which results. Another boiling crisis criterion [61J] is also based on a model of coalescence of the bubbles to form a continuous vapor blanket. Madsen [57J] suggests that plotting q_w vs ΔT in boiling using linear scales provides more insight into the physical phenomena of pool boiling and that such graphical techniques have usefulness in designing pool boiling experiments. Labuntsov [51J] gives an extensive survey of nucleate boiling of liquids. Bier deals with the same topic over a wide pressure range [16J].

Lienhard and Dhir [52J] generalize the hydrodynamic predictions of Zuber and Tribus of peak pool boiling heat fluxes from finite bodies. They also provide [53J] experimental verification of predictions of peak heat flux and q_{max} on horizontal plate heaters of finite extent in earth-normal and elevated gravity. Shih and Westwater [84J] describe predictions of spheres, hemispheres, and discs as high-performance fins for boiling heat transfer. Longitudinal fin systems on cylindrical shells are investigated [78J]. By using a tube with grooves, it is possible to favorably influence the shape of the characteristic boiling curves with respect to heat transfer and stability [42J]. Reference [41J] studies the effect of ill-wettable surfaces (strips of different surface material) on q_{cr}. Baumeister and Simon [13J] correlate information on the Leidenfrost temperature for liquid metals, cryogens, hydrocarbons, and water. A study [89J] of transient boiling around a sphere reveals three types of stable film backing and two methods of vapor film destabilization. Dhir and Lienhard [28J] study Taylor stability of viscous fluids in film boiling—taking into account transverse curvatures. Reference [82J] resolves questions on the Taylor wave configuration during boiling from a flat plate. Saturated film boiling of binary mixtures is analyzed [104J] using two-phase boundary-layer theory including diffusion and heat conduction in the liquid and demonstrating that large increases in film boiling may be obtained for mixtures with large relative volatility.

Five Russian papers discuss a variety of flow boiling features [93J, 97J–99J]. A boiling heat-transfer number is defined [94J] which is a measure of the maximum number of active nucleation sites. It is found from comparison of forced convection boiling annuli that q_{cr} values are different for heating of the inner and outer walls, a result due to differences in near-wall velocity gradients. Placing a swirl generator in an annulus substantially increases q_{cr} [74J]. A study of single phase swirl flow was extended to boiling conditions [54J] where swirl displaces the bubbles from the wall.

Basu [12J] gives evidence on the effects of electric fields on boiling hysteresis. Transient energy transfer under conditions of acoustic and high pressure loading have been studied [30J] by rapid laser heating of metal foils under water.

The effect of transverse convective motion of bubbles on the generation of additional surface bubbles is sometimes important [91J]. Data on surface film boiling under natural convection at low pressures are now available [31J, 72J]. Engineering equations are given [29J] for transient evaporation of a droplet at elevated temperatures with gas–liquid interface motion. A single analytical expression [24J] agrees to ± 15 per cent with the most all-inclusive numerical calculation of bubble formation along heated walls.

Modelling is of practical importance in reducing the high cost of critical heat flux testing for boiling water power reactors. A technique for fluid modelling of critical heat flux is developed from classical dimensional analysis and theory of models [3J]. There is interest in scaling q_{cr} in water using refrigerants [75J].

Relations for determining q_{cr} obtained with uniform surface heat flux cannot be used for the case of non-uniform heat addition [35J]. Reference [86J] investigates the region of applicability of the quasi-steady procedure for calculation of q_{cr} under dynamic conditions. Empirical relations are suggested [100J] for calculating q_{cr} for forced convection boiling of binary mixtures.

Since surface tension is an important parameter affecting nucleation in a boiling liquid, Shah and Darby [11J] investigate the influence of surfactant additives on convective boiling in a vertical liquid film. Experimental data are given for subcooled transient and forced convective film boiling from fine wires at low Reynolds numbers (30–300) relevant to the mixing and expansion stages of a thermal explosion [18J].

Condensation

Although only a monolayer of non-wetting surface promoter is required to attain dropwise condensation, many layers are often applied [101J] to ensure complete coverage which have appreciable thermal resistance. Experimental and analytical results [4J, 44J] point to the existence of very large heat-transfer rates around the perimeter of a condensing droplet and to the importance of the condensing wall as a heat-diffusing mechanism [6J]. For dropwise condensation at atmospheric pressure, conduction is the limiting resistance while at low pressure interfacial heat transfer is as important as drop conduction [37J]. Dropwise condensation is complicated [21J] by the existence of a very wide range of drop sizes, extending from the primary drops which form at nucleation sites and grow by conduction to the largest which can remain on the surface—being several orders of magnitude greater than the first kind [79J]. An approximate correlation was developed [33J] for the growth of drops during condensation in direct contact between liquid drops and vapor.

Dhir and Lienhard [27J] tabulate similar solutions for film condensation with variable gravity and body shape. Falkner–Skan mainstream solutions are also available in [14J]. Yang [102J] reports a boundary-layer approach for laminar film condensation over spheres and observes that a similarity solution can be obtained for the entire spherical surface if inertia forces are neglected. Marschall and Hickman [60J] deal with laminar condensation of vapors of immiscible liquids. An approximate integral method is used for binary mixture condensation on a cooled vertical plate [92J] that agrees within 10 per cent with the rigorous solution of Sparrow and Marschall. The heat-transfer performance in the range 1–99 per cent weight fraction of condensable gas on the free convection condensation around a vertical plate is shown in one figure [67J] having free convection and film condensation as two extreme limits. An integral method [32J] for determination of non-condensable gas behavior on a vertical surface for gases heavier than the vapor indicate a small effect of gas solubility on the condensate. Recent measurements [7J] indicate that when special care is taken to avoid convection effects, the effect of non-condensing gases in reducing condensation heat transfer is much greater than previously reported.

Linear stability theory is used to study the stability characteristics of condensate film flow down vertical [59J] and inclined [58J] walls. A critical Reynolds number is found that is so small that in most practical situations a laminar gravity induced condensate film is unstable. Account is taken of the temperature dependence of viscosity [76J] and of the non-linear temperature profile due to subcooling of the condensate. Using the relation $\mu = A\exp(B/T)$, Lott and Parker [55J] demonstrate that the effect of temperature-dependent viscosity on laminar viscosity becomes significant when $B > 1$.

Film condensation heat transfer is augmented by breaking the condensate layer with various non-wetting strips [34J]. Thermocapillary flow might be an important factor in determining the geometry of channeled condensate films [22J].

The use of a Blasius-type expression for the shear stress at the interface of a turbulently flowing vapor and a laminar condensate film, when applied to Nusselt's laminar film condensation analysis [62J], does not account for the large measured condensation rates with high vapor velocities. Reference [43J] clarified the existence of fog formation in the condensing vapor boundary layer over a flat plate. Condensing saturated mixtures of steam and helium, steam and air, and Freon-12 and steam, flowing turbulently in a pipe, agree [15J, 19J] with predictions of Kinney and Sparrow. The effects of variable fluid properties are emphasized in a study of condensation–evaporation kinetics in a binary vapor–gas mixture [69J]. Barrand [10J] shows that the unsteady discharge of a moist gas from a duct of adequate L/D is well adapted to the analysis of condensation phenomena. Condensation data in horizontal tubes with gasoline vapor

[105J], ammonia vapor [64J], Freon-12 [46J], and Freon-22 [23J] are available. In such tube flows for combined gravity condensate (co-current or counter-current flow) the local thickness of the film and its adiabatic mixing temperature were calculated [77J]. A high-rate condensation process theory is given [83J] for vapor flow inside a vertical cylinder. The control of the temperature in subcooling vertical condensers used in distillation columns has been found [9J] to be quite difficult and has caused off-specification products and excessive utility consumption. Schrodt [81J] develops a model for the multi-vapor–gas cooler–condenser problem which is solved numerically for both the horizontally and vertically aligned condensers [17J]. Data on condensation onset, shape of intense phase conversions, and particle dimensions are given [80J] for steam condensation in supersonic nozzles.

Two-phase flow

Experiments [25J] of unsteady wall pressure fluctuations for upward flow of a vapor–liquid Freon mixture in a pipe show strong attenuation of incident pressure disturbances generated within the turbulent two-phase flow, and axial disturbance propagation velocities 1·4 times the average mixture velocity. An exact solution is given [36J] for flow transients in two-phase systems using the method of characteristics that is considered simpler to use than the slip-flow analysis. Multiphase, multicomponent flow issuing from a cavity following an underground nuclear experiment [68J] has been investigated analytically. Nguyen and Spedding [71J] generalize the Dukler analysis of gas–liquid two-phase systems. The role of swirl generators on non-Newtonian fluids in pipes is investigated [88J]. Twisted tapes of low pitch used with gas–liquid mixtures increase heat-transfer rates at constant pumping power [73J]. The current literature contains more than twenty proposed relationships for calculating boiling heat transfer of steam in pipes. Reference [8J] considers two types which are most prevalent. In [20J] extensive Russian results are given for heat transfer, hydraulic resistance, and crisis in tubes along with engineering recommendations.

Isachenko and Solodov [45J] summarize recent Russian work on direct contact heat exchangers and jet condensers. Mills and Chung give an analysis for evaporating falling films in which $h_c \sim Re^{0.4}$, in agreement with Chung and Seban data, instead of $h_c \sim Re^{0.2}$ normally applied [63J]. The intensity of boiling heat transfer for sea water with solids content 9620 mg/l is 25 per cent lower than for pure water under the same conditions [106J]. Theoretical and experimental results of sublimation freeze drying compare within 10 per cent [39J]. Luikov and Lebedev [56J] explain peculiarities of the sublimation mechanisms for radiative and conductive energy sources and under periodic and steady conditions. The application of high velocity water jets is recognized by the mining industry as an effective and economical means for tunnelling. In [103J] a frozen ground modelling heat-transfer study was made on a vertical water jet striking a cylindrical ice block suspended above the nozzle.

A "salt" method is used [70J, 90J] in low intensity boiling which consists of determining the salt content of the process at which a certain saturation is attained at the heated surface and unlimited growth of salt deposits begins. A microthermocouple is used [26J] to obtain information on the structure of boiling two phase flow under nonequilibrium conditions by giving the local void fraction, the time average temperature in both phases, and their fluctuations. Harms and La Rotta give an analysis [40J] on the dynamic bias in radiation techniques used to study two-phase flows. An accurate electro-diffusion method is used to obtain local friction distributions along and around a tube [50J]. Experimental verification of an analytical model of temperature fluctuations in two-phase flow are obtained by the amplitude and frequency analysis of a microthermocouple signal [1J, 2J].

RADIATION

Radiation in participating media

Radiative transport in gray and non-gray media continues to attract great interest. In addition, there is a substantial number of papers devoted to problems involving simultaneous conduction and/or convection with radiation.

A new method is proposed for an approximate solution of the integral equations associated with radiation transfer in a finite-length cylinder filled with an absorbing, gray medium [35K]. The results of a study of the transient cooldown of a gray, absorbing, isotropically scattering, emitting and conducting medium, bounded by gray, diffusely emitting and reflecting parallel plates, clearly demonstrate the feasibility of computer solutions of transient energy transfer problems in materials in which scattering is significant [39K]. Theoretical studies of resonant wave motion of a radiatively active, non-conducting, gray gas, confined between two infinite parallel walls, indicate that around resonance frequency and for a sufficiently weak relative level of spontaneous emission, the nonlinearities in spontaneous emission give rise to shock waves which are repeatedly reflected at the walls [19K].

The results of studies of the emittance of semi-infinite, absorbing, and isotropically scattering media with refractive indices greater than unity indicate that the directional and hemispherical emittances can be either smaller, because of interface reflection, or larger, because of scattering, than those associated with media of a unity index of refraction [4K]. The effects of radiation on heat transfer and temperature distribution are investigated for the thermally developing region of an absorbing, emitting, and isotropically scattering slug flow inside a parallel plate channel with reflecting boundaries [26K]. An exact analysis of the hemispherical reflectivity and transmissivity of an absorbing, isotropically scattering slab with a reflecting boundary demonstrates that the reflectivity of the slab is slightly higher with a specularly reflecting boundary in comparison to a diffusely reflecting boundary [27K]. Asymptotic expressions for the directional and hemispherical emittance of an isothermal, isotropically scattering medium are presented and their usefulness is demonstrated for large optical thickness and albedo as well as for small optical thickness or albedo [10K].

In order to extend band emissivity data of ammonia reported in the literature to total emissivity values in a temperature range from 300 to 1000°K, a correlation and extrapolation procedure is proposed which yields quite good agreement with the suggested values of Port [37K]. Calculations of the emissivity of CO_2 and H_2O vapor in slabs of varying temperature indicate that the overall radiant flux of a mixture of CO_2 and H_2O vapor is the sum of the fluxes of the individual components. If the reduced beam path length is approximately the same for both components, corrections are required which take overlapping of the bands into account [30K]. Atmospheric thermal emission is measured with a digital recording near-i.r. spectrometer. Data for the lower atmosphere in a wavelength range from 2·5 to 4·2μ indicate that the HDO band is the major emitter in the 3·5–3·8μ region [21K].

Refractive index measurements are performed for ethane, carbon dioxide, and isobutane for temperatures from 100 to 250°F at pressures up to 1500 lb/in^2 and the compressibility factors derived from the results of these measurements compare favorably with published values [6K]. Absorption and emission of a medium are described in terms of converging series for a spectral band as well as for the entire spectrum. The ensuing equations are verified for the case of water vapor [11K]. An approximate method for describing absorption in high temperature gases is proposed. The agreement between calculated and experimental data is excellent for the total band absorptance of the 4·7μ band of CO [29K]. Theoretically determined values of absorption in the 4·7μ band of CO at high temperatures are in good agreement with experimental data [28K]. A theoretical closed-term expression for the total band absorptance of i.r.-radiating gases is shown to produce results which are in good agreement with theoretical values of Hsieh and Greif [20K].

Analytical studies of radiative cooling of a turbulent flame front show that CO_2, being an intense emitter, reduces flame front temperatures to a greater degree than H_2O, a less intense emitter, even though the total emissivity of H_2O exceeds that of CO_2 [14K]. Refractive indices of flame product gases measured in the far i.r. and electron densities obtained from Cesium-seeded flames show that existing theories do not apply at these wavelengths in the higher temperature range [25K]. Studies of the OH-radiation intensity and of the flame velocity of inhibited premixed methane–air flames corroborate the assumption that the primary action of the inhibitor is associated with a heterogeneous anti-catalytic effect [23K]. Generalized expressions for the calculations of the emissivity, absorptivity and other relevant radiation properties of H_2O, CO_2, CO, NO, SO_2, and CH_4 are readily applicable to solve combustion gas radiation problems [13K].

Data referring to scattering of thermal radiation by carbon particles in flames show that the scattering characteristics depend on the wavelength as well as on the particle size [7K]. Studies of radiative heat transfer in gas–solid suspensions with a radiating fluid in a circular tube assuming constant wall temperatures show that for laminar flow the heat-transfer characteristics can be substantially improved [12K].

Measurements of the heat transfer through a plane layer of fused quartz under conditions where the radiative transport is important compare favorably with analytical results based on a multi-band spectral model [2K]. Measurements of the spectral emission coefficients of quartz glass at temperatures from 500 to 900°C in a wavelength range from 3–14μ show that the emission coefficient normal to the surface decreases with increasing temperature displaying minima near 9 and near 13μ [34K]. The results of normal-incidence spectral reflectance measurements of ice at -7°C in the range from 300 to 5000 cm^{-1} are suitable for use in Mie-theory computations of scattering by ice particles in planetary atmospheres [33K].

Accurate values of the absolute specular reflectance at normal incidence for systems consisting of one or more absorbing films on an absorbing substrate may be obtained by extrapolation of experimental data to the angle of normal incidence using analytical predictions which are derived in this paper as a guide [31K]. Investigations of the thermal radiative properties of an air–water interface for a wavelength range between 0·2 and 200μ show favorable agreement with available data for emittance and absorptance [3K]. A highly sensitive ellipsometer is described which is suitable for measuring of the optical constants of interfaces between two bordering media [5K].

In studies of the coupling of conductive and radiative heat transfer through semitransparent solids (glass or silicon-like materials) the significance of bounding walls, of the absorption spectrum and of the band model used for the analysis has been demonstrated [1K]. In an absorbing, emitting and isotropically scattering medium at high temperatures, the energy transport within the medium by thermal radiation becomes important and the evaluation of temperature distributions in the medium requires a simultaneous solution of the equations for conductive and radiative heat transfer [8K].

A numerical study of combined radiative and convective heat transfer from hot air flowing over a flat plate reveals that radiative heat transfer has a strong effect on the Stanton number [38K]. Based on studies of combined radiative and turbulent forced convective heat transfer of gaseous suspensions of fine particles in circular tubes, it is concluded that the heat-transfer characteristics can be substantially improved, i.e. the temperature gradient becomes steeper at the walls while the gas temperature increases in the core of a pipe due to heat transfer from the radiation-absorbing fine particles [36K]. Analytical studies of simultaneous non-gray radiative transfer and turbulent diffusion in a layer of molecular gas enclosed by parallel black walls show the effects of self-absorption by cold gas close to the walls and the coupling between non-gray radiation and turbulent diffusion [15K]. A modified Patankar–Spalding finite-difference procedure is utilized to obtain numerical solutions of the integro-differential equations which govern the behavior of turbulent, high-speed, radiating boundary layers [17K].

Analytical and experimental studies of simultaneous radiative and free convective heat transfer along a vertical plate indicate that the heat-transfer characteristics can be evaluated by simple summation of radiation and convection [22K]. The interaction of thermal radiation and free convection in the boundary-layer regime of a vertical enclosure is examined. Experimental data for pure NH_3, pure N_2, and N_2–NH_3 mixtures for pressures up to 2 bar at a temperature level near 300°K are compared to a boundary-layer type analysis based on the exponential wide-band model [9K].

The results of coupled ablation–radiation studies of viscous hypersonic shock layers provide a sound basis for an understanding of the processes characteristic of hypersonic shock layer heating [18K]. Dielectric materials having densely packed internal scattering centers act as volume reflectors for incident radiation even when the exposed surface is eroded by thermochemical ablation. Teflon shells may withstand radiant fluxes up to 20 kW/cm² for approximately 5 s and fritted quartz up to 50 kW/cm² for approximately 8 s [24K].

The decay of perturbations in an infinite, thermally radiating gas of perfect electrical conductivity in the presence of magnetic fields proceeds, for a broad range of Boltzmann numbers (dimensionless convection–radiation parameter), from being a constant density cooling process to being a constant-pressure cooling process [32K].

Considering radial radiative heat fluxes in a cylinder the authors of this paper conclude that results of previous studies based on an approximation, are substantially in error for optically thin conditions, but that they are valid for the optically thick case [16K].

Surface radiation

Analytical and experimental methods for the determination of radiant properties and of radiative heat transfer have been reviewed [1L].

Radiation properties were measured for a number of surfaces: Spectral emissivity of tungsten in the visible region at temperatures between 1200 and 2600K [11L], spectral radiation properties of calcinated heating surfaces occurring in furnaces at temperatures from 1000 to 1500C [8L], total emissivity of tungsten at temperatures between 3000 and 2500K [5L], total emissivities of molybdenum at temperatures between 1100 and 2800K [10L, 12L], total emissivities of pyrolytical silicon and zirconium carbides at temperatures between 1200 and 2900K [13L], and monochromatic and total emittance of aluminum, brass and painted surfaces [7L]. The effect of thin films of gold and silver on monochromatic specular reflectance of perpendicular polarized radiation is reported [17L] at 10·6μ wavelength.

Radiation configuration factors for annular rings and hemispherical sectors are available [2L]. A Monte Carlo computation determined the apparent emissivity [6L] from isothermal baffled conical cavities. The apparent emissivity of a tubular mirror cavity with a slit aperture was analyzed [9L]. Directional emission from V-grooves and rectangular cavities was optimized [3L] providing a means to focus radiation. Formulas describing heat flow contours on a plane for parallel radiation reflected specularly from a cone, a hemisphere or paraboloid [15L], as well as for specular reflection from an arbitrary surface to an arbitrary receiver surface [4L] are available. Stability and convergence of the Monte Carlo method are improved [14G] by partitioning the energy of a ray bundle into two portions. A numerical calculation of combined conduction, convection, and radiation from a plate with internal heat source demonstrates that conduction in the plate can become important [16L].

LIQUID METALS

The results of measurements of temperature and eddy diffusivity profiles in NaK flowing through tubes with uniform heat flux at Reynolds numbers from 26 000 to 302 000 can be expressed by the following equations for the local and average Nusselt number [6M]:

$$Nu_x = Nu_\infty\left(1+\frac{2}{x/D}\right) \quad \text{for} \quad x/D > 4$$

$$Nu_{\text{ave}} = Nu_\infty\left(1+\frac{8}{L/D}+\frac{2}{L/D}\ln\frac{L/D}{4}\right) \quad \text{for} \quad L/D > 4$$

(Nu_∞ Nusselt number for fully developed condition).

The effect of streamwise heat conduction on heat transfer from a nonisothermal flat plate at low Prandtl numbers was analyzed [5M], assuming the wall temperature to increase proportional to the nth power of the distance from the leading edge. An analysis [7M] of the effect of non-condensable gas on laminar film condensation in liquid metals included the interfacial resistance. Experiments with sodium flowing turbulently through an annulus with gradual increase of the inlet temperature [1M] established the superheat for incipient boiling. Heat flux, flow rate, and rate of temperature rise had a strong effect [2M]. Experiments with alkali metals [3M] established the peculiar behavior that the transition from free convection boiling to film boiling occurs at low pressure without an intermediate nucleate boiling range. Four regions of heat transfer were identified in an experiment [4M] in which quartz-coated hot film probes were moved vertically through mercury at the presence of a horizontal magnetic field. It was also observed that the formation of Karman vortices was delayed and reduced.

MEASUREMENT TECHNIQUES

Development activity continues in a number of areas related to heat transfer. These include temperature measurements, heat-transfer measurements including the introduction of mass-transfer analogies, and in related fluid velocity measurements using both probes and optical techniques.

Liquid crystals have been used to map the temperature field near a heated surgical probe [3P]. A polymer capable of absorbing a volatile swelling agent can be used to determine mass-transfer rates and from these heat transport [15P]. Another mass-transfer analogy uses mercury evaporation to infer heat-transfer results [17P].

A probe has been developed to determine the temperature and concentration distribution in combustion gases by spectrometric means [6P]. The surface temperature of moving gas turbine blades was determined with film thermocouples [21P]. Several Russian works considered the design and operation of heat flux transducers over a range of temperature conditions [8P, 9P, 14P].

A hydraulic analogy has been developed to study heat transfer, in particular related to the fire endurance of building elements [12P]. A multi-beam interferometer has been developed for heat-transfer studies [16P]. The effect of light deflection on errors in interferometric studies has been assessed [2P].

Better visualization of boundary layer flow is obtained by observing the paths of oil particles over a surface with a schlieren or shadowgraph system [20P]. A commercial detergent which contains impurities is useful for the visualization of the very slow motion of water in enclosed spaces [19P]. A DOP aerosol generator has been described for use in the visualization of gas flow phenomena [11P].

Developments continue in hot wire anemometry and related equipment. Questions have been raised as to the accuracy of heat flux probe measurements in boundary layer flows [23P]. A careful study of the influence of orientation on aerodynamic effects of X-wire anemometers has been presented [22P]. Measurement of the response of hot wire anemometers in flows of gas mixtures has been recorded [18P]. A generalized law for determining the velocity from the output of a conical hot film anemometer includes buoyancy effects [10P]. Calibration of a hot film anemometer in low velocity mercury flows was maintained even after repeated immersions through a clean mercury fluid interface [13P].

Developments continue on optical measurements of fluid velocity. A detailed analysis of laser–Doppler velocimeters for use in turbulence flow has been presented [7P]. A special ultrasonic cell has been developed to use in measuring two-dimensional velocity fields [5P]. Application of laser–Doppler velocimetry included back scattering systems for measurements in a compressor rotor passage [24P] and measurements in a pulsating flame [4P]. An optical system using a Ronchi grating to form fringes in a flow field has been used to measure fluid velocity in a manner analogous to laser–Doppler systems [1P].

HEAT-TRANSFER APPLICATIONS

Heat exchangers and heat pipes

A considerable number of papers was devoted to heat exchangers. The effect of non-uniform velocity [8Q], of non-uniform heat-transfer coefficients on the heat exchanger surface [6Q], and on fin surfaces [21Q] was analyzed. Simplified calculation methods are presented in [5Q, 28Q], and experimental results are reported for a sintered-copper heat exchanger [24Q] and for tubular heat exchangers with Kaolin and coal slurries flowing through them.

Heat-transfer intensification also found considerable interest. Grooves around the periphery of the tubes are reported [14Q] to decrease weight and volume of the heat exchanger with no increase in pressure drop for flow of water. Photos of rough heat-transfer surfaces were obtained [22Q] with a scanning microscope fresh and after some use. Other papers deal with intensification through metal grids [33Q], through interrupted fin surfaces [9Q], and with the effect of surface roughness of fuel elements in gas cooled reactors [31Q]

The deterioration of heat transfer by frost formation [17Q], by oxide films on boiler tubes [18Q], and by calcareous film deposits [10Q] from water found attention. Equipment has sometimes to be overdesigned by 30 per cent because of fouling. A calculation method [26Q] of heat transfer to the rod bundle in a nuclear reactor divides the flow area into sub-channels and treats each channel one-dimensionally, considering exchange between the channels by turbulence.

Analysis and experiments studied heat transfer in regenerators [19Q, 23Q]. Heat transfer in cooling towers has found attention [1Q, 12Q, 20Q, 32Q]. Very effective cooling is obtained by spraying a liquid into a hot gas stream [11Q].

Laminar flow in heat pipes was analyzed [3Q, 4Q, 15Q] with special attention directed towards the flow limits. An analysis of the sonic limit in sodium heat pipes [16Q] finds that dissociation and recombination have no large influence. The Karman–Pohlhausen method is applied to a water heat pipe with neon as a control gas [27Q]. Gas loaded heat pipes were also studied [25Q, 29Q]. Electrohydrodynamic heat pipes are proposed [13Q] for the operating range between water and liquid metal heat pipes. The degradation of heat pipes by generation of non-condensible gases was predicted [2Q] with the help of an Arrhenius model for the chemistry of the process. Experiments studied the startup of high temperature heat pipes [30Q].

Aircraft and space vehicles

Ablation, heat shield performance, and other thermal protection systems for space missions are discussed in a number of papers.

Heat transfer and ablation-rate correlations for reentry heat-shield and nose-tip applications are derived. Predicted data for heat-transfer, ablation rates, and indepth temperatures obtained with two different approaches are well in agreement with each other and with flight thermal data [15R]. Graphite ablation under combined convection and radiative heating is studied in an arcjet facility at convective heating rates of 0·6–0·8 kW/cm^2, radiative heating rates up to 2·9 kW/cm^2, with test specimen surface pressures of 0·06, 0·1 and 0·3 atm in an air stream. The experimental and analytical mass loss and surface temperatures agree well when properties from the JANAF tables are used in the analysis [22R]. The re-entry shape change and indepth thermal structural responses of contemporary low-recession graphite nosetips are analyzed from the principal viewpoint of surviving thermally induced tensile strains [17R]. It is usually assumed for a graphite probe entering a planetary atmosphere that the composition of carbon vapors in the ablation layer adjacent to the wall corresponds to local thermochemical equilibrium. An analysis shows the significance of C_2 and C_3 concentrations on the optical depth of the ablation layer. If graphite is to be a candidate for thermal protection in strong radiative environments more information on the C_3 molecular absorption spectrum is needed [12R].

Studies of the ablation mechanism of a silica-reinforced composite reveal that the void fraction has a substantial effect on the heat of ablation and the presence of gas bubbles affects the apparent viscosity, the effective thermal conductivity, the carbon–silica reactions, and the flow pattern of the molten layer [9R]. Expressions for the temperature field in an ablator–metal composite material are derived which provide a description of the ablation dynamics useful for engineering calculations [16R]. Results of calculations of the stagnation region including the radiative flow field with steady-state ablation during Venus entry using high-density phenolic nylon as ablation material show that, at entry velocities around 10 km/s, reasonable estimates of stagnation region radiative heating rates may be obtained from simple analyses which ignore nonadiabatic effects in the shock layer and the absorption of shock layer radiation by ablation products [19R]. Measurements of temperature distributions in the boundary layer of an ablating, hemispherical nose cone of asbestos-filled plastic exposed to an air rf-produced plasma flow demonstrate that the boundary layer separates due to the injection of ablating vapors and, at the same time, the convective heat flux is reduced [7R]. In order to compensate for surface recession of ablating models in high-pressure, hyperthermal arc tunnels, a laser activated compensator-system, has been developed [24R].

A method is developed which calculates laminar, transitional, and turbulent heating rates on space shuttle-type configurations at angle of attack in hypersonic flow. Results for blunted circular cones and a typical delta-wing space shuttle orbiter at angle of attack indicate that the present method yields accurate laminar heating rates and reasonably accurate transitional and turbulent heating rates [6R]. A proposed approximation for maximum centerline heating on lifting entry vehicles (space shuttle) responds rapidly to inputs of altitude, velocity, and angle of attack with reasonable accuracies of predicted heat-transfer rates [8R]. For the evaluation of the thermal performance of RSI panel gaps for space shuttle orbiters, an arc ground-test facility is used to study the effects of local heat transfer in these interface areas. The results show that unfilled gaps run hotter than comparable undisturbed areas and for transverse and axial gaps, a trend of decreasing temperatures with decreasing gap width is evident [2R]. In connection with space shuttle, the range of Mach numbers and Reynolds numbers has been expanded to assess their effect on orbiter/tank interference heating. The primary effect of interference in the present tests is to cause transition to fully developed turbulent flow [5R]. Measurements of both the surface convective heat-transfer rate and pressure on the beryllium nose cap of the NASA Ames Planetary Atmosphere Experiments Test (PAET) are shown to be within 5 per cent of theoretical predictions [21R].

Thermal scale modelling of radiation–conduction–convection systems applied to the spacecraft cabin atmosphere/cabin wall thermal interface leads to the conclusion that either mass flux or heat-transfer coefficient preservation may result in adequate thermal similitude depending on the system to be modelled. Heat-transfer coefficient preservation seems to be particularly suited for manned spacecraft modelling [18R]. A flight test correlation technique for turbulent base heat transfer with low ablation is proposed for conical re-entry vehicles which proves to be adequate for engineering design predictions over a wide range of bluntness ratios and free stream conditions [4R]. The results of an experimental investigation of base heating rates are less than 2 per cent for the Viking shape (140° cone) based on the reference sphere heating [25R]. Reduction of the base-drag particularly at certain critical stages in the flight plan of a supersonic aircraft may be accomplished by base-burning. A method is presented for calculating the inviscid flow field with heat addition in an axisymmetric arrangement with burning behind a blunt base simulating actual base-burning [3R].

In connection with Apollo flights the effects of circular geometry in simulating of convection in rotating spacecraft tanks are studied. The results show that appreciable mixing can be achieved in a short time by small rotation maneuvers to prevent pressure collapse [14R]. Analytical and experimental investigations of natural convection in aircraft fuel tanks caused by external heating of the wings in supersonic flight demonstrate that the anslysis is capable of predicting the fluid motion and heat transfer with remarkable accuracy [13R].

Experimentation with silicone fuel additives in the N_2O_4–MMH and N_2O_4–A-50 propellant systems for thrusts from 500 to 6000 lb at 100–200 lb/in^2 chamber pressure and 16000 lb at 500 lb/in^2 indicates heat-transfer reductions of more than 30 per cent [1R]. Leading-edge turbulent heat flux predictions obtained from a two-dimensional thermal model of a fin calorimeter are in satisfactory agreement with flight test calorimeter data [11R].

Experimental and analytical studies of a typical 20 cm-dia, hollow-cathode ion thruster show that detailed temperature measurements in conjunction with a corrected thermal network model of the thruster allow a realistic description of thruster thermal performance [23R].

A semi-empirical correlation is established which predicts with reasonable accuracy the magnitude of film heat-transfer coefficients required for the design of cold plates for electronic equipment [20R].

A thermal analysis of a belt-type radiator by the method of matched asymptotic expansions provides information on temperature distribution and heat-transfer capacity [10R].

General

The use of evacuated thermal insulation of porous silica aerogel for thermal control was studied [6S]. The temperature rise in the inlet region of the rollers in bearings is attributed [5S] to the change in oil film thickness. Convective heat and mass transfer in drying and evaporating equipment can be increased by increase of the velocity, by turbulation, and by interruption of the boundary layer [7S]. Experimental results indicate that heat transfer in quenching is practically at quasi-steady state [11S]. Analysis and experiments [9S] provide information on the temperature field in a mountain during well sinking. An excellent review [4S] and experimental results [8S] in a fire of aviation fuel were reported.

Convective heat transfer from the human form can be predicted [12S] with the aid of experiments on cylinders or on an aluminum statue with one-fourth normal size. A prediction of the daily and seasonal thermal behavior of the desert iguana was compared with experimental results [1S]. The importance of the cardiac system for the heat transfer in biological tissue is demonstrated [3S, 10S]. The density, thermal conductivity, and enthalpy of human blood during freezing were calculated and checked by experiments [13S], measuring the time history of the temperature in a capillary tube filled with blood. A parametric study can guide the design of implantable blood heat exchangers for artificial hearts [2S]; up to 50W have to be removed.

Energy production

Calculations have been reported of the temperature field in steam turbine rotors [5T], of the temperature distributions in the rotors of multi-stage axial gas turbines [2T] with uncooled blades, and of the blade temperature in a gas turbine [11T] for a sudden timewise change of the gas temperature. It was demonstrated [4T] that information obtained in stationary equipment can be used to predict heat transfer in cooled flow passages of turbines. Prediction of heat transfer in furnaces of pressurized steam generators were compared with experimental results [8T]. Results of industrial tests [3T] on steam turbine condensers provided guides for improved designs and operation. The coolant behavior in a sodium cooled nuclear reactor was analyzed [1T] as it follows a fuel failure. Ammonia, Freons R21, R113, and water were investigated [7T] for combined gas vapor power plants of 1 to 3MW output.

New measurements at high altitude established the value of the solar constant as 1·94 cal cm^{-2} min^{-1} [10T]. The long term effects of pollutants in the atmosphere on solar insolation are discussed [9T] in a review. To duct air between the two glass windows of a solar collector before entering the absorber increases the efficiency by 10–15 per cent [6T].

PLASMA HEAT TRANSFER

Heat-transfer studies in plasmas reported during the past year refer to fundamental investigations, as well as to applications, in particular, to those associated with electric arcs.

The energy flux from a hot plasma to a cold wall, assuming that the plasma is exposed to a strong magnetic field parallel to the wall, may be approximated by an analytical expression derived from fundamental equations [4U]. Local heat fluxes to bare Cu tubes as well as pyrex-coated tubes immersed into a highly ionized flow of atmospheric pressure argon plasma are the same within experimental accuracy. Comparisons of experimental results with analytical predictions show that frozen chemistry prevails in the boundary layer surrounding the tube [10U]. For the measurement of plasma-wall heat-transfer rates, a spherical probe (thermocouple) is immersed into an atmospheric pressure argon plasma jet. Floating probe heat-transfer rates agree reasonably well with Back's theory and in the case of a negatively biased probe 65 per cent of the Joule heat generated around the probe is transferred to the probe [7U]. An analysis of coupled radiation with turbulent convection in electric arcs shows that even for high Reynolds numbers, the effect of turbulence is small compared to the effect of radiation at high currents. Turbulence, however, has a significant effect on radiation flux distributions and it also increases, as expected, wall heat fluxes [13U].

Local fluid constriction by gas injection into a wall-stabilized, rotationally symmetric arc increases temperature and specific enthalpy of the plasma and at the same time, wall heat fluxes to the constrictor tube are substantially reduced [5U]. Heat flux measurements to a segmented, biased wall of an electric arc chamber reflect the behavior of the corresponding current-voltage characteristics. The heat flux characteristics provide a sensitive criterion for the detection of electrical breakdown between plasma and a biased segment [11U]. An approximate similarity approach is applied to derive dimensionless relationships which describe the performance of various plasma torches including electrode heat fluxes [14U].

Measured characteristics of a transpiration cooled argon arc reveal agreement with theoretical predictions for the parameter range for which laminar flow can be maintained. In particular, the data show that the heat flux to the constrictor wall decreases with increasing mass flow in contrast to the behavior for turbulent flow conditions [8U]. Arc ignition with a transpiration cooled anode indicates abnormally high current densities during the first seconds accompanied by correspondingly high local heat fluxes. Melting of porous tungsten can be eliminated by proper control of the ignition sequence [15U]. Studies of transpiration cooling of the anode in a high intensity arc show that the temperature distribution through the porous material (graphite) depends only on the transpiring mass flow rate and on the pressure drop [1U].

Studies of the anode heat transfer in arcs with superimposed axial flow show that the anode arc attachment is not circular and the average local heat fluxes depend strongly on the pressure [12U]. A simplified analysis of the anode region of a high intensity arc provides an assessment of the relative importance of heat conductance and gas entrainment for the observed arc constriction in front of the anode and the associated anode spot formation [3U].

Measurements of electrical conductance and of gas temperatures in AC atmospheric, cylindrical arcs in air during the current-zero period are reported for arc currents in the range from 8 to 24 A and bore diameters of 0·5 and 1·0 cm of the confining disks. In contrast to findings of other investigators, the results of this study seem to indicate that the arc column is approximately in LTE [6U].

The nature of the thermodynamic expansion process in a highly cooled convergent–divergent nozzle is analyzed for an argon plasma flow by evaluation of the polytropic exponent from measured heat flux data to the wall [2U]. Measurements with a spectral scan with a modified Rotational Temperature Device (RTD) of nitrogen temperatures in arc tunnel air flows are found to be repeatable and consistent as long as the flow within the nozzle core is viewed [9U].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Thermodynamics

A number of papers deal with the structure of thermodynamics and the characteristics of certain systems. Thus Meixner [62W] considers the fundamental inequality in thermodynamics; Ellis and Chao [23W] consider the thermodynamics of nearly-ideal systems, and Winnick [93W] treats the thermodynamics of simple polar liquids.

Phase boundary properties are studied by Spencer and Danner [81W] who report an improved equation for prediction of saturated liquid density and Lu *et al.* [58W] who present a generalized correlation of saturated liquid densities. At high temperatures and densities, Baker and Swift [6W] develop theoretical expressions for the thermodynamic properties of gases at these conditions and report numerical results for hydrogen. Blau *et al.* [10W] treat equilibrium constant estimation and model distinguishability.

In a continuation of a comprehensive study begun earlier, Rowlinson and co-workers predict the thermodynamic properties of fluids and fluid mixtures, treating first critical and azeotropic states [85W] and applications [38W]. Continuing in the area of mixtures, Brunet [12W] reports on the thermodynamics of multicomponent reactive non-uniform systems as pertains to adsorption, and Lieberman and Fried [57W] estimate the excess Gibbs free energy and enthalpy of mixing of binary, non-associated mixtures.

In the critical state area, Straub [82W] presents an equation for the critical isotherm of real gases; Li's paper [56W] predicts critical temperature of azeotropes; Breedveld and Prausnitz [11W] discuss the thermodynamic properties of supercritical fluids and their mixtures at very high pressure; and Horvath [42W] gives a correlation of the critical properties of halogenated hydrocarbons.

Neilson and Crawford [64W] discuss the efficiencies of various thermodynamic processes.

Experimental investigations of thermodynamic properties cover a wide range of properties and systems. Sengers and Greer [55W] consider for steam, certain thermodynamic anomalies near the critical point; Koernak and Feldman [47W] study the velocity of sound in the two-phase flow of the refrigerant R-12. The density and thermal expansion of liquid metals rubidium and cesium up to 1300°C are reported by Basin [7W] as well as the values of these properties for cesium near the fusion-solidification point [8W]. Good [34W] reports enthalpies of combustion for nine organic nitrogen compounds related to petroleum, and Ensor and Anderson [24W] report on the temperature dependence of the heats of dilution of NaCl.

Carbon dioxide appears to be the target of a rather comprehensive experimental effort. Altunin and Coworkers report on isobaric specific heat values for carbon dioxide near the saturation line [2W] and on the Joule–Thomson effect [3W]. The speed of sound at low frequencies in the 1–40 kg/cm^2 pressure range is given by Gruzdev and Slavnyak [37W]. Lee and Mather [54W] report a useful compilation of data on the substance. Similar summaries of thermodynamic data are provided by Harrison *et al.* [40W] for compressed gaseous methane and by Kubicek and Eubank [51W] for *n*-propanol.

Phase equilibrium data are reported for a number of systems. Kondrat'ev and Parfent'eva [48W] report the vapor pressure of saturated potassium vapor and Gibbard and Scatchard [33W] the vapor–liquid equilibrium of synthetic sea water solutions from 25–100°C. Another investigation in this general area deals with the effects of experimental errors on thermodynamic consistency and on representation of vapor–liquid equilibrium data as reported by Ulrichson and Stevenson [88W]. Shilyakov [79W] describes certain singularities in the behavior of the interphase boundary near the critical point.

Considering mixtures, Fredenslund and co-workers [27W] give gas–liquid equilibrium of the oxygen–carbon dioxide system; Ray and Nemethy [73W] the density and partial molal volume of water–ethylene mixtures; and Malashenko *et al.* [61W] the principal thermophysical properties of binary mixtures of hydrogen and oxygen with water vapor. Wichterle and Kobayashi report vapor–liquid equilibrium data for methane–x mixtures: methane–ethane [92W], methane–propane [91W], and methane–ethane–propane [90W], all at low temperatures and high pressure. Yarborough [95W] considers vapor–liquid equilibrium data for multicomponent mixtures containing hydrocarbon and non-hydrocarbon components.

A number of papers touch on a variety of unrelated topics in this general area. There is an experimental study of the surface tension of melts of alkali alloys by the combined method as reported by Kiriyaneko [45W], the calculation of the enthalpy and entropy of combustion products of ash bearing fuels at high temperatures by Garkusha and Shchegolev [30W]. Datta [15W] proposes an addition to the standard psychrometric chart and Fomichev *et al.* [26W] study the melting temperature of corundum as a secondary reference point of the temperature scale. Holste and co-workers [41W] detail the effects of temperature scale differences on the analysis of heat capacity data; the specific heat of copper over the range 1–30K receives consideration.

Transport properties

Interest in this area runs to the behavior of dense fluids, mixtures, calculation schemes, and the measurement and compilation of data for a variety of systems.

Hanley *et al.* [39W] analyze the transport coefficients for simple dense fields by applying the modified Enskog theory. Applying the corresponding states concept, Lucas [59W] presents a new formulation for treating the transport properties of pure dense fluids. Doan and Brunet [18W] employ the same principle to consider the transport properties of liquid mixtures (n-paraffins). Berrondo [9W] treats chemical relaxation as a transport process and Park *et al.* [69W] use a heat-transfer measurement scheme to determine atomic recombination rates.

For calculating thermodynamic and transport properties of complex chemical systems, Svehla and McBridge [83W] present a Fortran IV computer program; Krivoshey [50W] describes a method for determining the temperature dependence of thermophysical properties of materials using an analog computer.

Filippow [25W] surveys the recent works carried out at the Molecular Physics Chair, Physical Faculty, Moscow State University. Described here, is a new method for simultaneously measuring all thermal properties of metals at high temperature. Results are presented for eleven solid refractory metals from 1000–1500 to 2500–3000°K, and thermal property results for liquid metals at high temperature are summarized and discussed.

Selected studies are directed toward special systems. Cremers *et al.* [14W] report on thermal characteristics of the lunar surface layer; Karpinos and co-workers [44W] give physical properties for hot extruded tungsten–copper pseudoalloys, and Shashkov *et al.* [78W] present data on thermophysical properties for thermal insulating materials in the cryogenic temperature region. In a related work, Kostylev and co-workers [49W] describe experimental investigations and give results for the thermophysical properties of thermal insulation materials under *vacuo*. The thermophysical properties of filled plasticized polyvinylchloride are reported by Dushcheko *et al.* [19W].

In the area of diffusion phenomena, Pommersheim and Ranck [71W] measure gaseous diffusion coefficients using a Stefan cell. Modifying the Stefan cell, Frost and Amick [29W] describe results for gas diffusion measurements. The prediction of binary diffusion coefficients for polar gas mixture is presented by Nain and Ferron [63W]. For moderately dense gases, Oost *et al.* [67W] discuss thermal diffusion in mixtures and the pair–correlation function. Van Loef [89W] treats the temperature and density dependence of the self-diffusion coefficient in simple liquids.

Thermal conductivity investigations include the theoretical work by Lakkad *et al.* [52W] which considers this property for a statistically isotropic heterogeneous medium, and studies such as that by Dijkema and co-workers [17W] who describe methods of measuring thermal conductivity and give results for gas and gas mixtures. Roetzel and Schaber [76W] present Schmidt and Prandtl numbers for binary gas mixtures. Tauscher [84W] predicts gas thermal conductivities for halogenated methanes. For the specific refrigerant R-21, Gruzdow and Shestova [36W] give thermal conductivity values for the liquid and gas phases. Experimental measurements for propane and n-butane in the range 300–1000K are reported by Ehya *et al.* [21W]. Using a thermal comparator method, Powell and Groot [72W] give values of thermal conductivity for three organic series: normal alcohols, acids, and saturated hydrocarbons. At high temperatures and pressures, Le Neindre [65W] describes the experimental results obtained for thermal conductivity for a number of fluids.

Evidence of interest in two-phase systems is shown by Akgerman and Gainer [1W] who predict gas–liquid diffusivities and Deshpande and Couper [16W] who report on the thermal conductivity of two-phase systems. Grief *et al.* [35W] consider the diffusivity of oxygen in a non-Newtonian saline solution. Continuing in this vein of rather specialized but interesting systems, Yamkawa and co-workers [94W] analyze the effective thermal conductivity of moist granular beds; Lapshov and Bashkatov [53W] give thermal conductivities for coatings of zirconium dioxide as applied by the plasma sputtering method. In the area of solids, Cheng *et al.* [13W] deal with the thermal conductivity of two- and three-phase heterogeneous solid mixtures; Pashayev and co-workers [68W] measure the same propetry for some alloys of the systems bismuth–lead and bismuth–antimony during fusion; and Schmidt [77W] reports thermal conductivity of uranium dioxide and uranium plutonium dioxide at high temperature. For the substance indium, Pashayev and Magomedov [70W] treat the thermal conductivity for both solid and liquid states. Values for technical iron are reported by Neymark *et al.* [66W]. Dymov and co-workers [20W] give thermal and electrical conductivity of graphite obtained by thermomechanical processing in the 8–2500K range.

A number of works deal with the thermal conductivity of graphitized, porous, or fibrous materials of special design. Zeigarnik and Peletskie [96W] investigate experimentally the thermal conductivity of graphitized materials. For porous materials, Fritz and Kirchner [28W] present data on thermal conductivity, Koh and Fortini [46W] predict thermal conductivity and electrical resistivity for metallic materials. The same properties are considered at high temperatures for loose and fibrous graphitic carbon materials by Einger *et al.* [22W]. Fiber metal wicks (sintered), saturated with liquid are investigated experimentally to determine their thermal conductivity by Singh and co-workers [80W]. Complex semiconduction compounds in the solid and liquid state are examined for thermal conductivity values by Amirkhanov *et al.* [5W]; Rocha and Acrivos [75W] consider the effective thermal conductivity of dilute dispersions.

In the viscosity area, Maitland and Smith [60W] present a useful reassessment of the viscosities of eleven common gases taking into account the accuracy of various results. Data is reported for a number of substances. Tkachev *et al.* [87W] study the viscosity of refrigerants R-22, R-114 and R-318; Altunin and Sakhabetdinov [4W] report measurements for liquid and gaseous carbon dioxide at temperatures 220–1300K and pressures to 1200 bar; Kaplun *et al.* [43W] study bismuth viscosity using a vibration method. Near the solidification temperature, Genrikh and Kaplun [32W] report viscosity data for the alkali metals, and Genrikh [31W] viscosity for alloys at high temperatures. The relationship between liquid viscosity and other thermal properties is taken up by Rivkin [74W] and Timrot and Serednitskaya [86W] call attention to the anomalous behavior of steam viscosity.

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