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HEAT TRANSFER—A REVIEW OF 1977 LITERATURE

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INTRODUCTION

THIS review surveys results that have been published in various fields of heat transfer during 1977. As in the past, the number of papers published during that period was such that only a selection can be included in this review. A more complete listing of papers is available in the heat-transfer bibliographies published periodically in this journal. The reviews published during the years 1970–1975 have also been reprinted as Volume 8 of the series *Progress in Heat and Mass Transfer* and include a comprehensive author and subject index.

A symposium on turbulent shear flows held on 18–21 April, 1977 at Pennsylvania State University included papers on the effect of turbulence in jets, boundary layers, wakes, plumes, and channels, including turbulent energy transfer. Proceedings of the conference are available. The Third International Symposium on Plasma Chemistry was held on 13–19 July, 1977 in Limoges, France. Plasma heat transfer was discussed in connection with processing of ceramics, chemical synthesis, and coal gasification. Diagnostics of thermal plasmas using spectroscopy and laser methods found attention. Proceedings can be obtained from the University of Limoges, Allée André-Maurois, Limoges, France.

The 17th National Heat Transfer Conference brought together researchers and engineers interested in various fields of heat transfer. The majority of the sessions were organized around engineering applications. Jerry Taborek, who received the Donald Q. Kern Award, presented an invited lecture on the evolution of heat exchanger design techniques, and E. M. Sparrow, the recipient of the Max Jakob Memorial Award, discussed heat transfer in complex duct flows in a second invited lecture. The papers presented at the Conference are available as reprints and many of these will be published in the *Journal of Heat Transfer* or in the volume *17th National Heat Transfer Conference, AIChE* papers.

The 1977 International Seminar organized by the International Center for Heat and Mass Transfer in August, 1977 in Dubrovnik, Yugoslavia was devoted to heat transfer in buildings and covered thermal and moisture transfer properties of structural materials, solar radiation, district heating techniques, air movement inside and outside of buildings, and heat storage. The proceedings of the conference will be published by Scripta Book Company, Washington, D.C.

The 98th Winter Annual Meeting of the American Society of Mechanical Engineers included 14 sessions on heat transfer, mainly organized around various engineering developments. Only two of the sessions were devoted to basic transfer processes, one dealing with heat transfer in solids and the other on turbulent flows. A panel discussion dealt with mechanical design problems associated with heat-transfer equipment. Reprints of the papers are available from ASME Headquarters in New York and many of them will be published in the *Journal of Heat Transfer*.

The 1977 International Solar Energy Congress was somewhat delayed and was held on 16–21 January, 1978 in Vigyan Bhawan, New Delhi, India. The papers presented at the conference were organized around the subjects of international and national programs, solar radiation and energy storage, flat plate collectors including solar ponds and concentrating systems, space heating and cooling, solar thermal power, wind power, and agricultural and industrial applications.

A number of books dealing with heat transfer or including heat transfer topics has appeared on the market. They are listed in the bibliographic part of this review. Volume 13 of *Advances in Heat Transfer*, published by Academic Press, New York in 1977, contains survey articles on heat and mass transfer between impinging jets and solid surfaces, in rivers, bays, lakes and estuaries, in porous media, and on viscous dissipation in shear flows of molten polymers.

Trends and developments in heat-transfer research during 1977 are characterized by the following highlights: Heat conduction was studied analytically and numerically, especially in situations including phase change. Complex flow configurations in channel flow caused by corrugations, spherical and cylindrical blockages, and partially constricted inlets, as well as fluids containing additives and particulate materials, found special attention. Variable property effects and freezing of flowing liquids in ducts were investigated.

Unsteady flow and heat transfer in laminar boundary layers has been studied by various analytical techniques. Heat and mass transfer from cylinders in crossflow continues to be a topic of interest. Experimental and theoretical studies were concerned with the effect of surface roughness and free stream turbulence. Packed and fluidized bed heat transfer found worldwide attention in several papers. Detailed measurements of the fluctuating velocities and temperatures in turbulent flow have been made and sophisticated models of turbulence were developed and applied to various flow situations. A very large number of papers considered natural convection, especially in porous media, with the development of insulations and geothermal energy extraction as a focus. A large number of papers, especially from the Soviet Union, considered heat transfer in boiling or condensation occurring in various applications.

Radiative transport in emitting, absorbing, and scattering media including particle suspensions found attention. Research activities increased substantially in heat transfer associated with thin films. Radiation properties of various solid substances were reported and the effect of surface roughness was studied. Measurement techniques were developed for flow and temperature measurements, especially in two-phase flow.

The literature on heat exchangers is still growing with attention focused on the development of surfaces leading to high performance devices, on improved calculation methods, and on the analysis of heat exchanger networks. Research activities, on the other hand, declined on ablation and thermal protection systems. Models to analyze flat plate and concentrating solar collectors and the solar flux arriving on the earth's surface were developed. Plasma heat transfer found particular interest in connection with chemical and material processing, as well as in arc circuit-breaker research.

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 this category.

CONDUCTION

The current literature on heat conduction contains a strong focus on problems of phase change. A substantial interest in solution methodology, both analytical and numerical, is reflected in recent publications.

Heat conduction has traditionally been assumed to be the sole transport mechanism in phase change problems. However, in an analysis of melting about a vertical cylinder, it was demonstrated that natural convection induced by temperature variations in the melt region is the dominant mode of transport [61A]. An extensive survey of analytical methods for solving heat conduction problems with moving boundaries was focused on the Soviet literature and contains over 250 references [35A]. The introduction of high conductivity particles into a solidifying low conductivity material aids the solidification rate but diminishes the heat of fusion per unit volume [58A]. If a hot liquid is suddenly poured over a relatively cold solid, simultaneous freezing of the liquid and melting of the solid may occur [25A]. A sphere of molten heat-generating material, initially at its fusion temperature and thereafter subjected to surface cooling, may either completely solidify, temporarily solidify and then remelt, or have a solid outer crust with an inner molten core [21A]. A sudden temperature change at the boundary of a moist porous material activates a moving interface which separates wet and dry portions of the material [54A]. In the analysis of teflon ablation, account was taken of crystalline–amorphos phase transition, thermal expansion, and formation of higher-molecular products [29A].

Solutions for transient conduction without phase change can be employed to predict the surface heat flux and interface position in phase change problems provided that the conduction solution is evaluated using suitably defined effective properties [17A]. Biot's variational principle was employed in solving a one-dimensional phase change problem with surface convection and radiation [72A]. The method of matched asymptotic expansions successfully solved the problem of solidification of a slab of finite thickness [66A]. With the Stefan problem reformulated as a set of coupled nonlinear integral equations, a large-time expansion for the position of the phase boundary was developed [36A]. For the solution of moving boundary problems, a stationary grid of finite elements was used in conjunction with special elements involving finite element models defined by discontinuous interpolation [67A]. The treatment of thermal boundary conditions in the finite difference solution of freezing problems has been examined via experiments on model and actual biological systems [18A]. Conventional integral transform techniques have to be generalized to accommodate the unknown interface position in phase change problems [48A]. The success of the isotherm migration method in tracking the movement of a two-dimensional quench front underscores its potential applicability to phase change problems [24A]. An implicit finite difference scheme was also shown to be effective in solving the two-dimensional heat equation during quenching [5A].

The Heat Balance Integral solution for solidification of a continuous casting shows that the neglect of axial conduction can lead to serious errors at low casting speeds [56A]. By application of simple transformations to available Heat Balance Integral solutions for the freezing of circular cylinders, spheres, and uniform prisms, results can be obtained for ellipses, rectangular prisms, and ellipsoids [23A]. Two Heat Balance Integrals, respectively obtained by integrating the heat equation and its first moment, were applied to the freezing of a cubit [51A]. An upper bound on the time required to freeze a layer of given thickness has been deduced from the Heat Balance Integral [37A]. A Heat Balance Integral formulation suitable for modeling polymer melting processes in a screw extruder took account of sensible heat, temperature dependent viscosity, and viscous heat generation [28A]. As an innovation to the Heat Balance Integral as applied to finite regions without phase change, the integral condition is used to find an exponent in the approximating polynomial [22A].

Various transient problems were solved in direct response to applications. In order to diminish the heat leak through current-carrying cables which energize superconducting magnets, the cable may be cooled axially by a stream of helium gas which runs counter to the conduction heat flow. The temperature in the cable can be determined from a one-dimensional transient conduction model [8A]. Metallurgical changes during heat treatment of alloys can result in significant changes of thermal conductivity [26A]. As an alternative to experiment, finite differences have been used to calculate the temperature history of fire-exposed protected steel columns [38A]. The time-dependent temperature distribution in multilayer metal oxide—semiconductor structures with internal heat sources was determined by an implicit numerical formulation [59A]. A Laplace-transform solution for the transient thermal behaviour of a sphere situated in a large surrounding medium was evaluated for liquid sodium entrained in UO_2—the motivation being a hypothetical accident in a fast breeder reactor [19A]. For a UO_2 fuel rod with zirconium cladding, the conjugate heat-conduction problem for the rod and cladding was solved by Laplace transforms, with account being taken of non-ideal contact [57A].

Other studies of transients were concerned with methodology as well as with potential applications. A finite-difference technique using data from a single embedded thermocouple was added to the arsenal of methods available for solving the inverse problem of transient heat conduction [69A]. Another recently published method is based on iterating the analytical solution which relates the time varying temperature at the internal measurement point with the Biot number corresponding to the unknown surface heat-transfer coefficient [42A]. The Kirchhoff transform followed by a series expansion enabled the unsteady heat equation to be solved for the case of variable thermal conductivity [63A]. Variable thermal conductivity effects in transient conduction can also be dealt with via an iterative scheme which is based on the (separation of variables) series solution for the constant property case [41A]. The variational embedding method enabled an approximate analytical solution for transient conduction in a semi-infinite solid with variable thermophysical properties [10A]. Upper bounds have been found for transient conduction in a rod, one end of which exchanges heat by radiation (i.e. nonlinearly) with the surroundings [49A]. The temperature response of a cylindrical surface to periodic time variations of the surface heat flux was determined via Duhamel's integral [20A]. Periodic steady state solutions can be obtained directly, without having to determine the decaying initial transient which precedes the onset of the periodic steady mode [45A]. Transient heat-conduction problems with special classes of source terms can be subdivided into a source-free transient plus a steady state part [44A]. Optimal control theory was employed to find the heat input to the face of a semi-infinite solid in order to keep the face temperature close to a prescribed value [47A].

Several papers dealing with steady conduction have been published. The heat conducted through a stack of parallelograms separated by thin partition walls increases as the parallelograms become more inclined [16A]. For fluid flow through a tube or over a wire with a heat-transfer coefficient which depends linearly on the wall temperature, axial conduction in the tube wall can combine with the heat-transfer coefficient variation to produce nonuniform steady-state axial temperature distributions [65A]. The thermal signature on an exposed surface due to a buried spherical heat source was determined with the aid of a transformation to a bispherical coordinate system [60A]. Exact and approximate solutions were obtained for a buried point or line source for the case of convective exchange at the exposed surface [43A]. Results for the steady-state temperature distribution in a solid cylinder moving in the direction of its axis through a crossflow of hot gas are applicable to the moving wire technique used to measure the heat-transfer characteristics of flames [32A]. The conformal transformation of an eccentric annulus into a concentric annulus facilitated steady-state heat-conduction solutions in the former [33A].

Fins continue to evoke some interest. The assumption of a uniform fin base temperature equal to that of the unfinned surface can lead to significant errors in the predicted fin heat-transfer rates [62A]. Optimum fin dimensions corresponding to internal heat generation have been determined for the rectangular fin [6A] and for the circular fin [50A]. To handle the time-varying temperature distribution in a radiating and convecting fin, a numerical procedure was employed whereby the spatial derivatives are represented by finite differences whereas the time derivatives are retained as such [11A]. Use of the theory of dual extremum principles led to approximate solutions for fins with variable heat-transfer coefficients and with radiative exchange and variable thermal conductivity [3A].

The complexity of conduction in anisotropic materials has called forth powerful mathematical methods as well as numerical solution procedures. Green's functions were used to good effect to solve for the transient and steady heat conduction in an anisotropic medium of a monocline system which is homogeneous in a circular cylindrical coordinates [14A, 15A]. Furthermore, Green's functions were also found to be effective for anisotropic media which are homogeneous in rectangular coordinates [13A]. A method which satisfies the boundary conditions in the least-squares sense was proposed for analyzing three-dimensional conduction in anisotropic solids of arbitrary shape [46A]. Finite difference solutions simulating the microwave freeze-drying of food underscored the importance of the anisotropic character of the material [4A].

Various aspects of thermal contact have been studied. When stacks of thin layers of tin-coated steel were compressed, the thermal resistance was inversely proportional to the compression per layer for freshly assembled stacks throughout the loading range corresponding to macroscopic conformity [2A]. The thermal constriction resistance of nonsymmetric contact areas is less than the corresponding resistance for circular contact [73A]. A correlation of all presently available data enables the prediction of thermal contact conductance for stacks of thin metallic layers in high vacuums [1A]. With a view to determining the constriction resistance, solutions have been obtained for the transient response of two semi-infinite bodies at initially different temperatures which communicate thermally through a small circular contact area [55A]. Measured contact conductances were compared with predicted values for cones pressing against plane surfaces [40A].

Numerical solution methods have already been mentioned in prior paragraphs of this section, and other numerically oriented papers will now be cited. Many algorithms used in transient heat conduction which are unconditionally stable for linear problems lose this property when applied to nonlinear problems [31A]. In predicting temperatures with an implicit finite difference method, there is a tendency for the surface temperature to oscillate if a non-linear radiation boundary condition is imposed; the oscillations were eliminated by an iterative procedure [70A]. The Crank–Nicolson noise encountered in the stiff equations resulting from the finite element discretization of the heat equation can be reduced by proper choice of the forcing function [71A]. New coarse-mesh methods for the numerical solution of steady conduction problems were developed by use of local Green's functions which convert the original differential equation into local integral equations defined in subregions of the original physical system [30A]. A square-grid finite difference procedure for solving Poisson's equation in a rectangle having a non-rational side ratio uses multi-point difference equations [52A]. A hybrid method based on the linking of a resistance–capacitance network and a digital computer has been proposed for solving problems governed by the nonlinear diffusion equation [12A]. The method of weighted residuals, which is used for obtaining approximate solutions for steady and transient heat conduction problems, has been augmented by the incorporation of Lagrange multipliers for satisfaction of both initial and boundary conditions [64A].

Theoretical work has continued on the hyperbolic heat equation and on materials with memory. Whereas the hyperbolic heat equation effectively explains the finite propagation velocity of heat waves, another explanation has been suggested on the basis of the finite time required for the molecular distribution function to approach equilibrium [9A]. Use of the method of characteristics for solving the hyperbolic heat equation enables greater flexibility with regard to boundary conditions and material properties than do available analytical solutions [68A]. The hyperbolic heat equation has been modified to accommodate distributed heat sources and change of phase [27A]. The conduction boundary-layer concept was used in the investigation of non-Fourier effects in solids having surface curvature [34A]. Non-Fourier effects in the melting of a semi-infinite solid were found to be confined to very small times and to a very thin layer near the surface [53A]. The mathematical attributes of linear and non-linear integro-differential equations for heat flow in materials with memory have been explored [7A, 39A].

CHANNEL FLOW

Recent studies of heat transfer in ducts reflect a strong interest in complex flow configurations, in fluids containing additives and particulate material, in variable properties, and in the freezing of flowing liquids. The nature of the thermally developed regime was re-examined, and new correlations have been proposed.

There are four types of thermal boundary conditions that are compatible with the existence of a thermally developed regime in constant area ducts. They are: (a) uniform wall temperature, (b) uniform wall heat flux, (c) convective heat transfer from the external surface of the duct and (d) axial exponential variation of the wall heat flux. The Nusselt numbers for uniform wall temperature and uniform wall heat flux are bounds for the Nusselt numbers for external convection. Furthermore, cases (a)–(c) are special forms of (d) [52B]. Generalized concepts of fully developed flow and heat transfer have been formulated for ducts of periodically varying cross section. The new concepts were illustrated by application to laminar flow and heat transfer in a heat-exchanger configuration consisting of successive ranks of plate segments placed transverse to the flow direction [38B]. A single correlation for the pipe flow Nusselt number, encompassing all Reynolds numbers (i.e. laminar, transitional, and turbulent) and all Prandtl numbers has been proposed by Churchill and compared with available experimental data [8B]. All the available turbulent heat-transfer results for tubes and channels having roughness elements in the form of regularly repeated ridge-like protrusions perpendicular to the stream direction have been brought together and correlated satisfactorily [24B].

A wide variety of complex flow configurations have been dealt with. Experiments showed that in the low-Reynolds-number turbulent regime, corrugation of a channel wall caused large increases in the heat transfer coefficient compared to a parallel plate channel, but only moderate increases occurred in the laminar regime [17B]. The wake behind spherical blockages in a turbulent pipe flow has a major effect on the downstream heat transfer at the pipe wall [28B]. Measured heat-transfer coefficients for a crossflow cylinder situated in a turbulent pipe flow are substantially larger than those for a crossflow cylinder in an unbounded low-turbulence flow [39B]. Mass-transfer experiments in laminar channel flow downstream of a partially constricted inlet indicated the presence of separation zones of different length on the respective walls. In addition, downstream of the shorter separation zone, a previously undiscovered region of high mass transfer was encountered [51B]. For radial outflow in a passage formed by two parallel disks, the heat transfer at the two disks differs because of flow separation adjacent to the inlet aperture on one of the disks [18B].

Solutions for laminar flow and heat transfer in channels whose walls are interrupted periodically along the stream direction demonstrated that such passages can provide superior heat-transfer performance when compared to a conventional parallel plate channel [50B]. Finite difference solutions have added laminar Nusselt numbers for I-shaped ducts to the available store of fully developed results [37B]. The Schwarz–Neumann technique enables fully developed laminar flow and heat-transfer results for complex duct shapes to be obtained from available series solutions for simpler shapes [59B]. Numerical solutions for laminar flow and heat transfer in internally finned helical coils indicate that $f\,Re$ is a function of both the Dean number and the radius of curvature, whereas the Nusselt number is a function of Dean number alone [32B]. The gain in heat transfer and the penalty in pressure drop have been measured in airflow for a longitudinal fin with various augumentation treatments which subdivides a rectangular channel into two parts [56B]. With the gas-cooled reactor as the motivating application, a transformation has been developed to generalize heat-transfer and friction data for a single roughened rod contained in a concentric smooth tube to predict results for a cluster of roughened rods [9B]. Flow acceleration caused by the sloping wall of a duct brought about the laminarization of an initially turbulent flow [55B].

Investigations were performed of liquid flows with additives, non-Newtonian and fluids with microstructure, and particle-laden gas flows. Predictions of heat transfer in drag reducing viscoelastic fluids in turbulent pipe flow were based on generalizations of Reichardt's model [25B] and of Cess' model [14B]; in both cases the predictions agreed well with experimental data. Electrochemical mass-transfer techniques were used to study the effects of drag reducing additives in a turbulent pipe flow. At a given volumetric flow rate, the percent change in the fully developed mass transfer was greater than the percent change in the pressure drop [33B]. From numerical solutions for laminar flow of a non-Newtonian power-law fluid in a square duct, it was found that when the non-Newtonian flow behaviour index is less than one, the heat-transfer coefficients are higher than those for a corresponding Newtonian flow [6B]. The laminar Nusselt number for fluids with microstructure depends on the ratio of the rotational viscosity coefficient to the shear viscosity coefficient [27B]. Droplet evaporation augments the laminar heat-transfer coefficients in the thermal entrance region of a parallel plate channel [3B]. The turbulent heat-transfer characteristics of particle-laden gas flows in ducts were explored in a series of papers that appeared in *Heat Transfer, Soviet Res.* [13B, 36B, 46B, 53B, 54B].

Variable properties and supercritical fluids have been studied. Numerical solutions for laminar flow of inert gas mixtures in a uniformly heated tube indicated that for design predictions, the property ratio method is better than the film temperature method for heat transfer while the latter method is preferable for apparent wall friction [34B]. The temperature dependence of the rheological properties can have a significant effect on heat-transfer rates and pressure drop when viscous fluids are heated or cooled in tubes [40B]. The implications of variable conductivity and specific heat on the correlation of turbulent pipe-flow heat-transfer results have been examined, but the assumptions of constant viscosity and Prandtl number limit the practical utility of the findings [21B]. Numerical solutions for turbulent pipe flow of supercritical helium gave higher heat-transfer coefficients at higher heat fluxes and when the inlet bulk enthalpy was above the pseudocritical value [44B]. On the other hand, measured heat-transfer coefficients for supercritical helium in both vertical upflow and downflow agreed with predictions of the Dittus–Boelter equation to within 20% [5B].

A number of papers with the freezing of flowing liquids. When a superheated liquid in laminar flow in a parallel plate channel is subjected to convective cooling at the walls, the thermal entrance region consists of a solidification-free zone followed by a zone where a solid grows inward toward the center of the channel [7B]. An analysis of the steady state freezing of a turbulent liquid metal flow adjacent to the cooled walls of a parallel plate channel led to a coupled convection–conduction problem for the liquid core and the frozen layers [47B]. To solve the related problem of transient freezing in a tube for a liquid initially at its fusion temperature, it was assumed that the turbulent velocity profile is adequately represented by the slug flow profile, the Blasius friction factor formula is applicable, and the shape of the frozen layer can be represented by a simple functional form [12B]. The latter assumption was subsequently lifted by solving an integro-differential equation [11B]. A variant of the tube or channel solidification problem is the freezing which occurs when a cold continuous sheet (or wall) is caused to move through a liquid environment [29B]. Dendritic ice forms in a pipe when there is no mainflow through the pipe during the freezing process. This ice form occurs because the quiescent water supercools considerably below 0°C before ice nucleation begins [15B]. Studies were made of the effect of this ice form on the pressure gradient required to start flow in a partially frozen pipe. It was found that under some conditions, the growth of dendritic ice in a pipe can result in a flow blockage when only a small fraction of the water in the pipe is frozen [16B].

Some interest still remains in axial conduction. An analysis of laminar flow in a parallel plate channel with uniform but unequal temperatures at the bounding walls shows that axial conduction at low Peclet numbers can cause a considerable increase in the thermal development length [57B]. Axial conduction in the channel walls bounding a turbulent flow was found to have heightened effects at low Prandtl numbers [43B]. Axial diffusion was also investigated for mass transfer in laminar pipe flow with chemical reaction, but no account was taken of possible diffusion upstream of the inlet cross-section [10B].

The effects of flow pulsations were investigated. The time-averaged fully developed Nusselt number for laminar pulsatile flow in curved pipes is larger than that for pulsatile flow in straight pipes [49B]. For pulsatile laminar airflow in a tube, low frequency pulsations caused a decrease in the heat-transfer coefficient whereas high frequency pulsations brought about an increase [31B]. Pulsatile laminar flow and heat transfer in a parallel plate channel with uniform injection and suction at the respective walls was studied with reference to the dialysis of blood in artificial kidneys [41B].

Several papers covered a miscellany of pipe flow studies. When the heating rate at the wall of a turbulent pipe flow is rapidly increased from an initial value to another value, the time variation of the fully developed heat-transfer coefficient takes on a maximum value before attaining steady state [26B]. The turbulent Graetz problem for a parallel plate channel was solved for Prandtl numbers between zero and 10^4. For Prandtl numbers greater than 0.1, the fully developed Nusselt numbers based on the hydraulic diameter agreed well with those for the circular tube, with lesser agreement at lower Prandtl numbers [48B]. The presence of constant heat sources and frictional energy dissipation in turbulent pipe flow reduces the rate of heat transfer [1B]. Laminar flow experiments in a heated tube with stepped streamwise variations of heat flux yielded Nusselt numbers that deviated by about 10% from analytical predictions [42B]. Local turbulent heat-transfer coefficients for the thermal entrance region of a pipe were measured for air flow under constant wall temperature conditions [30B].

General topics in laminar flow continue to be analyzed. An integral momentum–energy treatment of the simultaneously developing laminar velocity and temperature fields in a parallel plate channel employed a stronger integral constraint for the velocity, but the Nusselt numbers are very little affected [4B]. Extensive tabulations of local Nusselt numbers have been made available for laminar channel flow with finite external resistance, with [22B] and without [23B] magnetohydrodynamic effects. A method has been evolved for determining the wall temperature distribution required for the attainment of a uniform bulk temperature in a laminar pipe flow having temperature-dependent heat generation [35B].

Mass transfer in pipes, with special emphasis on high Schmidt number fluids, has been studied both experimentally and analytically. Experiments for turbulent mass transfer in pipes at high Schmidt number (1000–6000) indicate that neither the Colburn equation nor the Dittus–Boelter equation are good representations of the data in that range of Schmidt (or Prandtl) number [2B]. Other experiments encompassing Schmidt numbers up to 37 000 have established the dependence of the mass-transfer coefficient on the Schmidt number [45B], and this dependence has been affirmed by an algebraic turbulence model [19B]. The spreading of solute that has been injected into fully developed laminar pipe flow is governed by both diffusion and convection [20B, 58B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Theoretical and experimental investigations of laminar and turbulent boundary layers form the bulk of the studies in this category. Attention is also given to free-stream turbulence, impinging jets and flow over a cylinder.

The conjugate heat-transfer problem involving the laminar boundary layer on a plate of finite thickness is studied by the use of Lighthill's method of boundary-layer analysis [24C]. The laminar flow and heat transfer on a flat plate situated in the laminar wake of an upstream plate is analyzed by a numerical method [27C].

Among the theoretical analyses of turbulent boundary layers, an approximate local analysis is performed to solve the integral momentum equation for two-dimensional compressible boundary layers [17C]. Numerical solutions have been obtained for a turbulent boundary layer with variable physical properties of the fluid [31C]. The predictions are made by using a mixing length model and are compared with experimental data. Analytical expressions have been obtained for the temperature distribution in terms of the local velocity for turbulent boundary layers with non-unity Prandtl numbers [35C]. A theoretical analysis has been reported for heat transfer in turbine blades with longitudinal cooling slots [4C]. A formula is developed for the friction factor in turbulent flow of liquid films over vertical surfaces; then, by the Reynolds analogy, an expression for heat transfer for the same situation is obtained [5C]. A numerical solution of the flow and concentration field has been presented for a point source at the ground level of a turbulent shear layer. The effective viscosity is governed by one differential equation. The computed results are shown to agree well with available experimental data [25C]. Mass transfer between a turbulent flow and a wall with first-order chemical reaction is analyzed for large Schmidt numbers [14C].

An experimental study of the velocity and temperature fields is reported for the thermal layer that grows inside a turbulent boundary layer which is subjected to a step change in the wall heat flux [3C]. An interferometric investigation has been made of the temperature field created by a cold air jet issued inclined to an adiabatic flat plate in hotter ambient air [11C]. Detailed measurements of the turbulent flow field have been reported for a subsonic compressible turbulent boundary layer. These show that the ratio of the Reynolds stress to the turbulence kinetic energy depends on the Mach number [1C]. Reference [34C] presents an experimental study of a thick hypersonic turbulent boundary layer on a cooled wall. Experimental data on high-temperature free jets produced by burning the methane gas have been used to confirm a proposed extension of Prandtl's eddy diffusion model [15C]. Heat transfer from developing water film over cylinders has been experimentally investigated [23C].

Many papers have dealt with unsteady boundary layers. An anlysis has been made of the unsteady heat transfer from a plate in an incompressible flow [8C]. In another unsteady-heat-transfer study, the finite-difference solution of an integro-differential equation is obtained for a laminar boundary layer over a plate of finite thermal capacity and thermal resistance [32C]. The laminar thermal boundary layer in response to harmonic oscillations in velocity imposed on the free-stream velocity is analyzed. It is shown that the heat transfer is reduced for Prandtl numbers less than unity, and increased for Prandtl numbers greater than unity, due to the presence of the oscillatory free stream [30C]. Unsteady heat transfer in a thick thermal boundary layer over a spherical surface in random motion is studied in terms of the inner and outer regions of a boundary layer by a method of successive approximations [36C]. Approximate solutions using integral methods and the method of characteristics have been obtained for laminar boundary layers with a steady velocity field and a transient temperature field caused by a sudden change in the wall temperature [29C]. An analysis has been made for the transient heat and mass transfer at the surface of a dielectric drop in another dielectric liquid under the action of an electric field, for the low Reynolds number, high Peclet number situation [22C]. Heated laminar boundary layers have been experimentally studied for their stability characteristics by subjecting them to linear sinusoidal disturbances created by a vibrating ribbon [28C].

Among the investigations of the effect of free-stream turbulence, a laminar boundary layer is experimentally studied to find the influence of the free-stream turbulence on the velocity profile, the drag coefficient and other quantities [9C]. An analysis is performed for the effect of free-stream turbulence on heat and momentum transfer to axisymmetric bodies in supersonic and hypersonic turbulent streams. The turbulence is characterized by the turbulence kinetic energy (obtained from a differential equation) and a length scale (prescribed algebraically) [33C]. An experimental study is reported of the local heat-transfer coefficients influenced by the free-stream turbulence in a flow over a cylinder around the critical Reynolds number [37C].

Several investigations are directed towards the impinging-jet situation. A similarity solution has been obtained for steady laminar compressible three-dimensional stagnation-point flow with variable transport properties [20C]. An analysis is reported for the heat transfer in axisymmetric stagnation flow on an infinite circular cylinder for the constant wall temperature and constant wall heat flux boundary conditions [10C]. Experimental data have been obtained for the heat transfer from a continuously moving belt to an air jet impinging normally. The maximum heat-transfer coefficients are about 1.5–2.0 times higher than those predicted for the stationary surface [26C]. Mass transfer from a flat surface due to an impinging free jet from a rectangular duct has been measured by laser holographic interferometry [19C]. An experimental study has been made of the heat transfer from impinging circular jets to investigate the effect of the intensity of turbulence [13C].

The flow over a circular cylinder continues to be a subject of considerable interest. A single comprehensive equation is developed for the rate of heat transfer from a cylinder in cross flow covering the entire range of the Prandtl number and the Reynolds number [6C]. A correlation is presented for the recovery factor for the compressible flow of air over an infinite cylinder placed normal to the flow [12C]. From experimental data for drag on spheres and cylinders, the effective Reynolds number based on the Eckert reference temperature is found to correlate the drag data well [18C]. The heat- and mass-transfer coefficients to disks and cylinders in cross flow have been found from new experiments and compared with earlier results and available correlations [16C]. A model for the eddy diffusivity induced by free-stream turbulence is constructed and applied to the stagnation point of a cylinder in cross flow. The predicted Nusselt number and friction factor agree well with available experimental results [21C]. An experimental investigation of the heat transfer from a circular cylinder in cross flow has been reported, in which pyramidal roughness elements were used on the cylinder surface. The transition to turbulence has been determined as a function of the Reynolds number and a roughness parameter [2C]. An analysis has been presented for the mass transfer from a circular cylinder performing harmonic oscillations in a fluid at rest [7C].

FLOW WITH SEPARATED REGIONS

Single bodies

A systematic, unified, comparative analysis is made [9D] of all possible similitude rules pertaining to incipient separation-viscous interaction for both laminar and turbulent flows. A new regime of heat-transfer augmentation [24D] occurs at the walls of a channel with a partially constricted inlet; it occurs on the side washed by the short stall and is downstream of both the short and long stall reattachments. The laminar boundary layer and separation has been studied [28D] for a steady outer inviscid flow over an upstream moving wall. Consideration is given [23D] to the nature of the separation and subsequent reversed flow occurring when a jet-like boundary layer on a wall encounters a concave corner of finite angle. Two papers [18D, 19D] give analyses of the effects on the thermal boundary layer of the separation–reattachment zone that is induced in a supersonic flow by a slight hollow in the surface of a flat plate. Three-dimensional heat- and mass-transfer effects across high-speed reattaching flows are analyzed on the basis of a compressible, small disturbance flow model of the local vortex instability mechanisms involved [8D]. An experimental study of the turbulent near wake of a flat plate is given [1D].

Packed and fluidized beds

Much of the data for heat transfer from packed beds includes a length effect resulting from higher transfer coefficients near the inlet [13D]. The effective thermal conductivity of sheared suspensions is discussed [16D]. New dryout heat flux data for inductively heated particulate beds have now been obtained and semi-theoretical correlations suggested [4D]. Heat-transfer data in flowing, packed beds [3D] closely fit the predictions of the Mickley model which includes the role of the circulating particles. Pust [20D] analyzes sintered heat exchangers for throughflow helium cryostats. Concentration profiles are used to obtain actual driving forces in packed beds for $(0.1 < Re < 100)$ in order to evaluate axial and radial dispersion contributions to mass-transfer factors [7D]. Two papers [29D, 30D] describe and give a critique on the determination of packed bed particle-to-fluid heat-transfer coefficients from steady, radial measurements. Another paper [12D] distinguishes between two types of temperature excursions in adiabatic packed bed reactors: the hot spot and the unstable temperature runaway. A numerical analysis scheme is developed [10D] for the heat transfer in packed bed recuperators.

Much potentially useful energy is wasted because it is carried away by effluent gases containing contaminants which cause rapid fouling. A solution to this problem [21D] might lie in the use of a falling cloud of dense particles to extract heat in combination with a fluidized bed to remove the particle heat. Shallow fluidized beds have good potential as heat exchangers since the pressure drop is low enough not to require the use of large fans [2D]. McGaw [14D] describes the development of a mechanism for gas-particle heat transfer in shallow fluidized beds on the basis of experiments. A two-resistance model for heat transfer in aggregative and particulate liquid-fluidized beds [17D] agrees well with data. Mass-transfer data in liquid fluidized beds are in disagreement with some recent theories that predict an important decrease in mass-transfer rates at low Reynolds number [27D]. Experimental results are given [11D] for three phase fluidization in which solid particles are fluidized by the cocurrent flow of liquids and gases. The magnetic field was found [22D] to be an important parameter governing the fluidized bed structure when the solid particles are ferromagnetic. The application of an alternating electric field to cause movement of particles charged naturally in a fluidized bed has been demonstrated to increase heat transfer up to 140% for frequencies up to 100 Hz [5D].

The world-wide interest in various fluidized bed combustor systems is surveyed [6D, 25D]. In [15D] fluidization and gas combustion are studied in a rotating fluidized bed with centripetal acceleration of ten times gravity. Fluidized bed combustion is a possible method for providing the heat source for a Stirling engine because it is nearly isothermal at low temperatures and high heat flux rates [26D].

TRANSFER MECHANISMS

Various aspects of turbulent flows have been dealt with in papers on transfer mechanisms. These include detailed measurements, turbulence models and other theoretical analyses.

An experimental study reports measurements of the structure of isotropic turbulence generated by a water fall of low head: the measurements are made by the use of the hot-film technique [16E]. Hot-wire anemometer data are reported on some aspects of the fine-scale structure of turbulence in grid flows, in zero-pressure-gradient boundary layers, and in relaminarizing boundary layers [5E]. The spectral energy transfer of turbulent velocity fields has been examined over a wide range of Reynolds numbers by experimental and empirical methods [12E]. Measurements have been made of the turbulent flow in a rectangular duct of 12:1 aspect ratio using conditional-sampling techniques [7E]. Another rectangular-duct flow has been investigated by the use of a laser-Doppler anemometer; the axial mean velocity and turbulent intensity were measured in the developing flow, and all three mean velocity components and five of the six Reynolds stresses were obtained in the nearly fully developed flow [18E]. An experimental study of turbulence field in the near-wall region of a circular pipe reports the fluctuations of temperature and velocity, the length scales, and other correlations. The flow is found to be intermittent even within the viscous sublayer [9E]. Two-point turbulence data from hot and cold wire anemometry are presented which describe the temperature and velocity fields downstream of a heated grid in a low-speed wind tunnel [24E]. Statistics of temperature fluctuations are measured in a slightly heated boundary layer well downstream of a step change in wall heat flux [2E]. Reference [26E] reports the three components of the dissipation of the fluctuating temperature measured simultaneously in the inner region of a fully developed turbulent boundary layer. In a related study [3E], the probability density of the dissipation function is found to be log-normal even at relatively small Reynolds numbers. The eddy diffusivity near the free surface in an open channel flow has been determined by experiments around a Prandtl number of 3, and a model has been proposed for the calculation of the variation of the eddy diffusivity [27E]. Measurements have been presented for the influence of the Schmidt number on the frequency of the mass-transfer fluctuations at a wall in a turbulent flow [25E]. The effect of a drag-reducing additive on the structure of wall turbulence in a pipe flow has been investigated by hologram interferometry [1E]. Turbulence measurements in a rough-walled pipe flow have been reported and analyzed in a particular manner to show that the turbulence structure in a rough pipe follows the same scaling laws as for a smooth pipe [21E]. Hot-film anemometer measurements in fully developed pipe flow have been described; a procedure has been developed for identifying "bursts" in the wall layer [10E, 11E]. Artificially initiated turbulent spots in a Blasius boundary layer were investigated using hot-wire anemometers; the spots were generated by electric discharges [30E].

A number of papers are concerned with various types of turbulence models. For three-dimensional turbulent boundary layers, some simple algebratic expressions have been proposed for the eddy viscosity in the outer region [19E]. The predicted mixing lengths in the outer region of a turbulent boundary layer have been compared with those derived from velocity profiles [29E]. Various similarity theories for the atmospheric boundary layer have been critically examined in the light of numerical results and recent observations [4E]. A method for calculating turbulent diffusion in the planetary boundary layer is developed on the basis of Donaldson's second-order closure. The predictions of the model show good agreement with the laboratory data for diffusion in a free convection mixing layer [14E]. Detailed examination and comparison of four two-equation turbulence models have been made. The models have been applied to equilibrium boundary layers under various pressure gradients and to flow over a convex wall [6E]. Similarity solutions have been obtained for various free turbulent flows and duct flows by the use of a two-equation turbulence model; a set of universal constants has been obtained which gives satisfactory agreement with experimental data [28E]. For the general case of turbulent plane flow, local equilibrium solutions for a Reynolds-stress-transport turbulence model have been presented. The local equilibrium implies that the production of the stress balances its dissipation [20E]. Reynolds-stress models of turbulence are examined with reference to realizability conditions. It is shown that certain existing models do not guarantee realizable solutions. Suggestions have been made for changing the existing models into realizable ones [23E].

Among more fundamental studies of turbulence, a kinetic theory of turbulent flows is further developed [15E]. A discussion of the mechanism of entrainment in turbulent free shear flows concludes that entrainment is the folding of the turbulent and nonturbulent fluids by the rotation of the large eddies [8E]. The return to isotropy of homogeneous turbulence is considered in a theoretical investigation. The main assumption is that the changes are slow relative to turbulence time scales. Constraints on the governing functions are found by theoretical arguments. A convenient form is proposed for the functions, and it is shown that the predictions based on these are in excellent agreement with all available data [17E]. An estimate of the coefficient of self-diffusion is derived from kinematical consideration [22E]. A non-Newtonian viscosity is obtained for macromolecular liquids from nonlinear constitutive laws. The viscosity is found to decrease with increasing magnitude of the velocity gradient [13E].

NATURAL CONVECTION

Considerable research activity in natural convection is evident with a large number of analytical, numerical and experimental works considering various problems in pure natural convection and combined natural and forced convection both in internal flows and in boundary layer flows. As has been the case for some years now, there is much interest in heat transport in flow in plane layers heated from below. There seems to be more work being done on buoyant plumes. Considerable research is in evidence on natural convection in porous media.

An analysis presents lower bounds for the onset of instability in buoyancy-driven convection following an impulsive change in surface heat flux [106F]. Convection in a low Prandtl number fluid, in the limit as Prandtl number approaches zero, has been analyzed in a circular geometry [86F]. The effects of surface tension on the onset of flow in a fluid layer over an ice surface has been examined [91F]. A numerical analysis of Benard convection in a two-component fluid includes the influence of the Soret effect [83F]. The effect of side-walls in Bénard convection with roataion has been examined [29F]. A numerical solution of highly truncated modal equations yields the flow and temperature distributions over a range of Rayleigh number and Prandtl number for a horizontal layer heated from below [102F].

Natural convection in a volumetrically heated horizontal fluid layer with an adiabatic lower boundary has been examined at high Rayleigh number [20F]. In experiments using a similar geometry, the transient as well as the steady state heat transport are determined [55F]. The heat transfer and stability in volumetrically heated layers are analyzed with heating from below [23F].

The stability of longitudinal rolls in inclined plane layers has been analyzed [24F]. The reduction of natural convection heat transfer with the introduction of square and hexagonal structured honeycomb panels in inclined layers has been reported [8F]. A related study finds the ability of rectangular honeycomb to inhibit natural convection improves with tilt from the horizontal [1F].

The heat transfer and temperature distribution in an open tank of water heated from below have been measured [52F]. The heat transfer for moderate Rayleigh number convection of liquid metals in enclosures of different geometries has been calculated [28F]. The stability of a fluid in an inclined slot with simultaneous diffusion of heat and mass has been studied [13F]. Numerical predictions [80F] agree with flow visualization [81F] of the natural convection patterns in an inclined rectangular box heated from below.

A transverse temperature gradient influences the flow field in a low Prandtl number fluid heated from below [99F]. The temperature fields and heat transfer have been obtained for convection in an enclosure with heating on a side wall and/or on the bottom wall [44F]. A numerical study of natural convection in a box with differential side heating predicts three-dimensional motion [60F]. Finite element analysis has been applied to free convection in enclosures [100F].

An analysis of heat transfer by natural convection across vertical layers has been given over a range of conditions from conduction to turbulent flow [88F]. The effect of nonlinear variation of density with temperature in natural convection flows between two parallel vertical walls has been examined [104F]. A correlation has been obtained for the Nusselt number following the initiation of transient convection in vertical enclosures [4F]. An earlier analysis of convection between differentially heated side walls has been reconsidered [87F]. The finite element method has been used to study the natural convection flow between two vertical parallel plates [78F]. The presence of a solute can influence the heat transfer throughout a fluid in an enclosure with differentially heated side walls [108F]. A linearized solution of the natural convection in a vertical open tube has been presented [62F]. Unsteady natural convection in a vertical cylindrical cavity has been examined [68F].

Natural circulation within a horizontal pipe from one end has been described [45F]. Convection of low Prandtl number fluids within a horizontal cylindrical annulus gives a flow different from that found at higher Prandtl number; the center of rotation moves downward at higher Rayleigh numbers in the low Prandtl number fluid [27F]. Different flow regimes are observed over a range of Grashof and Prandtl numbers in the region between a sphere and its cubical enclosure [85F]. Different modes of motion are also described for convection in a hemispherical cavity tipped at various inclinations to the horizontal [75F]. Convection in helium I has been studied to simulate the heat transfer in rotating super-conducting windings [10F].

Interest in various stages of convection within porous media have expanded considerably this year. These include studies related to stability, developed convection, and applications. A linear stability analysis indicates the onset of convection in a fluid layer overlying a layer of porous media filled with the same fluid [77F]. Convective instability in porous media has been compared to that in a fluid with a concentrated suspension that is heated from below [105F]. Temperature dependent viscosity and thermal coefficient of expansion have been included in determining the critical Rayleigh number in an elastic porous matrix [67F]. The importance of aspect ratio has been demonstrated in determining the critical Rayleigh number in a water-saturated porous medium [111F]. The onset of flow and its characteristics in an anisotropic porous layer have been examined [34F]. A finite amplitude analysis treats thermal convection in a horizontal porous layer with internal heat sources [103F]. Another study finds anisotropy has little effect on natural convection in a porous layer other than in a nonhomogeneous stratified layer [11F]. Solutions for uniform heat flux to a fluid in a porous layer with natural convection are reported [15F]. A pH indicator method is used to visualize the flow in a Hele–Shaw cell to model thermal convection in porous media [43F].

Measurements of convection in a vertical slot filled with porous insulation indicate the heat transfer in common insulated building walls can be dominated by wall leakage [6F]. The effect of lateral mass flux in vertical free convection in a porous medium has been examined [17F]. A perturbation analysis is used to study natural convection flows in geothermal reservoirs [56F].

Numerical procedures are used to calculate natural convection from a confined heated horizontal plate facing upwards [107F]. Analysis has been applied to natural convection heat transfer from a hot plate facing upwards [2F] and downwards [3F]. The dependence on Grashof number of transitions and different plume modes have been established for natural convection from heated strips on a horizontal surface [5F].

The rough surface at a salt-brine interface yields a higher natural convection mass transfer rate than a smooth surface does [12F]. Thermohaline convection in the form of "salt fingers" is observed in the freezing of a saline solution [41F].

A perturbation technique is used to describe low Grashof number flow around a sphere in a thermally stratified fluid [94F]. Heat transfer from horizontal cylinders to different fluids is represented by somewhat different correlations depending on the choice of the reference temperature for evaluating the fluid properties [37F]. Laminar convection from horizontal cylinders of elliptical cross-section has been analyzed [63F]. The natural convection around a horizontal cylinder of ice with a density inversion in the surrounding fluid has been studied both theoretically and experimentally [89F]. The natural convection around a suddenly heated cylinder has been described [42F].

A number of studies relate to flow and temperature distribution in buoyant plumes both in the atmosphere and in the laboratory. Temperature and velocity profiles were measured in an axisymmetric buoyant plume [39F]. Velocity measurements in a plume above a horizontal line source were 20–25% smaller than that predicted by analysis [75F]. Prediction of turbulent plumes issuing into stratified or uniform ambients includes the effect of buoyancy on the turbulent transport model [59F]. The plume above a falling point source has been analyzed [26F].

The structure of free convection in the atmosphere near the ground surface is modeled as a field of plumes rising regularly from the surface [61F]. The initial Froude number is important in determining the entrainment characteristics of buoyant plumes in atmospheric inversions [35F]. A companion study considers turbulence properties to get entrainment into a plume [36F]. The release of thermal plumes appears to dominate the flow in the atmospheric boundary near the ground surface [101F].

A simple turbulence model is used in a numerical analysis [58F] to describe the curved trajectory of a buoyant jet. Another model is used to predict the trajectory and dilution of a buoyant jet in a cross flow [109F]. A model of a surface buoyant jet that enters normal to the stream is used to study the flow from the effluent of a power plant [74F]. A detailed study of the flow of a vertical plane turbulent buoyant jet includes measurements of the mean properties [54F] and the turbulent structure [53F] of the jet.

A technique is developed to predict the natural convection on a vertical plate with arbitrary wall temperature or heat flux [51F]. The effects of a very long vertical plate on laminar convection have been considered [73F]. The temperature and flow fields above a local heat source on a vertical adiabatic wall have been measured [9F]. An approximate solution considering variable gas properties has been obtained for laminar convection with uniform heat flux from a vertical plate [69F]. The effect of stratification in the surrounding fluid on the heat transfer from a vertical wall has been examined [49F]. An analysis of the flow arising from a line thermal source at the leading edge of a vertical adiabatic plate has been described [47F].

Two studies consider the transient natural convection from a vertical plate. In one [65F], the influence of variable properties is examined. The other considers time-dependent surface temperature or heat flux [66F].

A turbulence model has been applied to predict heat transfer from a vertical isothermal surface [84F]. The frequencies for growth of disturbances that influence transition on a vertical plate are found to be determined by frequency filtering [48F].

The natural convection mass transfer following an injection of pure water through a porous plate into an aqueous solution of sodium chloride has been measured [57F]. Unsteady natural convection flow past an infinite vertical plate has been analyzed with constant suction [97F] and with variable suction [98F] at the plate surface. The mass transfer from an upward facing, downward facing and an inclined flat plate has been studied using an electrochemical system [82F]. Experiments yield the temperature and velocity fields with natural convection over a vertical plate with a forward-facing step [46F].

Solutions for natural convection heat transfer from a vertical plate to a power law non-Newtonian fluid include the effects of variable gravity forces [40F]. Natural convection in curly-viscous fluids have been studied for constant wall temperature [92F] and for variable wall heat flux [93F].

Experimental data has been used to develop expressions for optimizing the geometry of fins heating the surroundings by natural convection [33F].

A number of studies consider combined forced and natural convection around a horizontal cylinder. A finite difference scheme was employed to solve equations for such a flow [71F]. For vertical forced flow across a cylinder, an analysis covers the range from pure natural to pure forced convection [70F]. With a vertical free-stream, heating the cylinder is found to delay separation while cooling the cylinder brings the separation point nearer to the stagnation region [64F]. The influence of free stream turbulence on mixed convection in a horizontal forced flow has been examined [90F]. With downward forced flow around a heated cylinder, periodic variations of heat transfer are found [76F]. Equations have been presented [22F] to correlate mixed convection from flat plates, spheres, and horizontal cylinders in the case of aiding flow.

The effect of natural convection Taylor–Görtler vortices along concave walls has been studied [50F]. For a forced flow parallel to an open heated cylinder, the effect of buoyancy on the convection on both the outer and inner surfaces of the cylinder has been analyzed [110F].

Local similarity and non-similarity methods have been used to predict the combined natural and forced convection boundary layer flow over a horizontal plate [14F]. The critical Rayleigh number for convection in a liquid film flowing over a horizontal plate has been determined [31F]. The effects of natural convection on the flow around an impulsively started plate has been analyzed [96F].

Similarity solutions are used to predict the mixed convection from horizontal impermeable surfaces in a saturated medium with both parallel and stagnation flows [16F]. A related study examines solutions in aiding and opposed flows [18F].

Studies on combined natural and forced convection in internal flows include a number of works with flow inside horizontal tubes. In the entrance region the influence of secondary flow [79F] and temperature-dependent viscosity [21F] on heat transfer have been studied. A finite-difference procedure has been applied to fully developed turbulent flow through horizontal tubes [95F]. Viscous dissipation is found to have a significant stabilizing influence on the flow of a high Prandtl number fluid in a horizontal channel heated from below [19F]. The enhancement of heat transfer with combined convection in internally finned square ducts has been demonstrated [38F].

For Coutte flow heated from below, instabilities can occur either as stationary waves or as waves which propagate along the convection rolls [25F]. The modal structure for combined convection with Couette flow has been described [30F].

An experimental study of heat transfer in a vertical tube with forced flow either upwards or downwards has been reported [72F]. A simple correlation for combined convection inside vertical tubes with either aiding or opposing flow has been proposed [32F].

CONVECTION FROM ROTATING SURFACES

Heat transfer in the entrance length of a horizontal rotating tube with laminar throughflow and cooling of the wall was found to be strongly reduced at rotational speeds above 40 per min [9G]. The effect of variable density on the stability of flow between two rotating cylinders was studied [6G]. It was found that instability starts with an oscillatory secondary flow and that Prandtl number has an effect on its onset. The electrochemical technique was used [3G] to study mass transfer in Taylor vortex flow. Axial throughflow was found to reduce the Sherwood number on the outer cylinder by 30–50%. Turbulent heat transfer was measured [5G] for flow through an annulus with inner cylinder rotation. A correlation between rotational and non-rotational Nusselt numbers based on a parameter characterizing the flow helix gave results in excellent agreement with the experiments. Laminar flow and heat transfer in a shrouded cylindrical cavity with a rotating and a stationary disk and a stationary cylindrical wall was analyzed [12G] with the result that heat-transfer coefficients increase with increasing coolant flow, decreasing rotational speed, and decreasing length to diameter ratio. A prediction [14G] of local heat transfer on a rotating disk using a two-equation model of turbulence agrees with experiments within 3%. Heat-transfer rates between a rotating disk and an eccentrically impinging jet were found [10G] essentially independent of jet flow rate in a rotationally dominated regime but to increase strongly with impingement rate in an impingement dominated regime. Fully developed heat transfer for steady, laminar, incompressible flow through a pipe rotating around an axis normal to the pipe axis was analyzed in [15G].

Two papers [4G, 11G] studied local heat transfer from rotating wedge shaped radial blades by an integral analysis and by mass-transfer experiments using naphthalene ablation. The cooling problem of alternators instigated experiments on pool boiling of liquid helium and heat transfer in supercritical helium in acceleration fields of 180–1720 g [13G]. The results could be described by the equation $Nu = 0.29\ Ra^{0.29}$. The desire to understand MHD flow in the earth's interior resulted in two papers [7G, 1G], on the thermal stability in a rotating spherical fluid shell with different distributions of heat sources. An exact solution [2G] of magnetohydrodynamic Couette flow and heat transfer with rotating surfaces indicates that on the moving surface the shear increases but heat transfer decreases with increasing magnetic or rotation parameters. Separation of gas mixtures can be obtained in the Lindstrom–Lang vortex tube. It was found [8G] that maximum separation is connected with a critical Reynolds number.

COMBINED HEAT AND MASS TRANSFER

Research in combined heat and mass transfer continues with considerable emphasis on cooling problems related to high temperature systems such as gas turbine plants. In this respect, considerable emphasis is focused on film cooling with somewhat reduced interest in transpiration cooling. Other efforts in the area of combined heat and mass transfer include the effects of thermodynamic coupling in boundary layers, combined heat and mass transfer in evaporation problems, and the influence of suction on wall heat transfer.

Studies of two-dimensional film cooling in which a coolant is ejected through a spanwise continuous slot concentrated on the effects of high temperature, streamline curvature, and high speed flow. When compared to the film cooling effectiveness on a flat plate, a convex surface yielded better results and a concave surface relatively poorer film cooling performance [11H]. The presence of blades was found to have little effect on the film cooling effectiveness over a cylindrical surface [17H]. For slot injection used to cool plates exposed to a high temperature gas stream, even very simple previously-developed semi-empirical relations could correlate the data well [15H]. Film cooling was found to be much more effective in a rapidly converging nozzle than in a gradually converging one [20H]. In a Mach 6 flow, a series of slots at different positions in the mainstream direction gave a better cooling effect than did a single slot for the same total mass flow rate [6H]. Numerical analysis and experiments on the heat transfer to a wall jet included the effects of injection through a slot as would occur in two-dimensional film cooling [9H]. Detailed measurements of concentration and mass flux in the turbulent boundary layer following slot injection of helium give insight into the processes that would affect two-dimensional film cooling [8H].

In many practical applications, the film coolant would be introduced through a series of discrete holes across the span of the surface to be protected. The characteristics of the flow and cooling effectiveness following injection through a round hole inclined at 30° to the surface, shed light on the film cooling performance very close to injection [2H]. A mass-transfer analogy is used to obtain experimental results on film cooling effectiveness over a large range of density differences between the mainstream and the injected fluid [16H]. The effect of using spanwise-angled holes at the leading edge of a turbine blade to introduce a film coolant has been investigated [5H].

Local non-similar solutions were obtained for the flow and heat transfer in a plane wall jet with mass addition along the surface [4H]. Experiments [3H] and an approximate analysis [19H] indicate the temperature profile and flow in the turbulent boundary layer over a porous wall with suction.

Comparison of the diffusion of mass and heat using the laminar and turbulent boundary-layer equations indicates the feasibility of using heat transfer to simulate mass transfer and vice versa [10H].

The heat transfer and skin friction with mass transfer in the region of a three-dimensional stagnation point [13H] were determined by the numerical solution of the steady laminar compressible flow boundary-layer equations. The effect of geometry on the heat transfer to impinging jets as occurs at the inlet edge of a turbine blade has been measured [1H].

Thermodynamic coupling in boundary layers has been studied with applications including injection of low molecular weight gases into boundary layers, ablation, and chemically reacting flows [18H]. Mass transfer in the vapor phase rather than heat transfer is found to be the controlling mechanism in distillation [7H]. An analytical study of heat and mass transfer includes processes involved in the evaporation of a liquid drop [12H]. Local non-similarity solutions have been obtained for heat and mass transfer from a subliming particle [14H].

CHANGE OF PHASE

Boiling

A step input of reactivity in a nuclear reactor will result in a power excursion in which reactor power rises exponentially in time. Two papers [42J, 43J] study incipient boiling superheat, boiling heat transfer, and burnout for such exponentially increasing heat inputs. A generalized equation for critical heat flux in free-convection boiling appears in [50J]. Overshoot temperature differences far in excess of normal boiling temperature differences were required to initiate boiling of refrigerant R-113 and methane in [20J]. The large superheats appear to be a characteristic of organic liquids of low surface tension and relatively low conductivity compared with water. The nucleation criterion hitherto used in predicting incipient boiling superheat seems wrong if gases exist [32J]. A possible mean number of nucleation sites is discussed [11J]. Naturally formed boiling site cavities are described [4J]. In [26J] the research work of the past ten years on the subject of incipient superheats in alkali metals is examined in view of the large discrepancies. A theoretical model has been developed [48J] to predict the frequency of bubble departure in nucleate boiling considering the effects of surface superheat and cavity size. Experiments [54J] verify the bubble growth model of van Stralen, *et al.* that combines the initial Rayleigh solution with a diffusion-type solution accounting for both a relaxation and an evaporating microlayer. A lengthy report [44J, 45J] is given on the formation of superheated steam bubbles, their size, shape and frequency of formation at high system P and T. The second part describes heat transfer during bubble formation. Experimental data on nucleate boiling in binary mixtures [47J] suggest that diffusion resistance plays a significant role in the reduction of heat transfer in aqueous systems and is the controlling factor in non-aqueous systems. Zÿl [58J] employs numerical methods to potential and unsteady viscous flow fields around a bubble. Subcooled nucleate boiling experiments [39J] demonstrate that heat transfer is controlled by bubble formation on the metal surface and not influenced by bubble implosions away from the surface. The effects of phase interface and surface tension on entropy, free energy, internal energy, enthalpy, free enthalpy and their differentials are reduced for droplets and vapor bubbles. These results are used to give the thermodynamic interpretation of vapor bubble collapse [37J]. A theoretical analysis of one-component vapor bubble collapse with translatory motion in a uniformly subcooled liquid has been carried out [6J]. Photographs demonstrate [31J] that there is nucleation associated with bubble venting when boiling occurs in thin liquid films. This has previously gone unrecognized. A correlation of nucleate boiling heat transfer is given [35J] based on bubble population density. Recent Russian correlations of burnout in annuli are given in [36J]. In [3J] a technique is given to construct a boiling curve from quenching data. A transient boiling heat-transfer crisis is described in [51J]. Measurement of transient surface temperature during nucleate boiling of water at high heat fluxes supports the view of many investigators that a liquid film, called the macrolayer, exists beneath the agglomeration of vapor bubbles and is paramount in transferring heat [57J]. A comprehensive experimental and theoretical study of dispersed flow heat transfer (post dryout) is given in [12J]. The mechanisms include transition and film boiling. Transition boiling with flow boiling inside a horizontal tube may always be operated under stable conditions and burnout does not occur [49J].

The pressure excursions which follow the sudden exposure of a hot body to a liquid pool have been the subject of several recent studies with the safety of nuclear reactors an important example. In [24J] the heat conduction arising from the saturation temperature's dependence upon pressure is shown to be important. In binary film boiling it has been shown [28J] that the liquid–vapor interface temperature depends on liquid mixture diffusion and omission of these diffusion processes might lead to erroneous heat-transfer results. Reference [7J] reports the rates of vaporization of liquid nitrogen and methane spilled on a water surface. Dua and Tien [8J] extend the works of Tien and Yao and develop a generalized two-parameter relation for conduction-controlled rewetting on a hot vertical surface. Ünal [53J] uses high speed photography to obtain good correlation of void fraction and incipient points of boiling during subcooled nucleate flow boiling of water. Effective cooling of a fast rotating drum can be obtained by evaporating a liquid flow as a thin film on a conical internal surface [40J]. The role of Taylor instability on the sublimation of a horizontal slab of dry ice placed beneath a pool of warm water or benzene has been observed [5J] and classified as pseudo-film boiling. In [9J] an analysis is given for stable, laminar, natural convection film boiling heat transfer from an isothermal flat circular plate facing downward and submerged in a saturated liquid. In [1J], vaporization effects of mercury droplets in Leidenfrost film boiling are measured—diffusion from the upper surface of the drop is a dominant mode of mass transfer.

Current literature describes forced convection boiling heat transfer as primarily convective heat transfer. The original evidence for this concept, reported by Dengler and Addoms is re-examined [30J] and found to be misinterpreted. Development strategy is given [14J] for model development of benchmark solutions to specially designed flow-boiling equations that closely approximate the true mathematical solutions. The heat transfer–controlled collapse of large, cylindrically-shaped water vapor bubbles rising due to buoyancy effects inside a vertical tube with constant wall temperature is dependent on tube diameter and fluid subcooling [38J]. Gradon and Selecki [13J] analyze evaporation of a liquid drop immersed in another immiscible liquid when the dispersed phase surface tension is greater than the continuous phase surface tension. When the drop is critically overheated, a thermal explosion takes place.

Condensation

In all practical situations, the average heat-transfer coefficients for laminar film condensation on semi-infinite helically-wound circular cylinders lie within 10% of values for inclined circular cylinders [22J]. Selected experiments on film condensation, including a noncondensable gas in an enclosed chamber [33J], have been carried out to clarify the effects of molecular weights of vapor and noncondensable gas and the convective motion induced by the vapor flow. An analysis is given [34J] for the condensation of saturated vapor on its laminar falling liquid sheet in which velocity and temperature variations in the transverse direction are included. A numerical method is used to calculate heat transfer into thermally-governed transient helium flow surges in two-phase condensing flow [56J]. Heat transfer during annular flow condensation of steam inside tubes is studied [52J], and with steam condensing on a cylindrical, laminar jet of water [18J].

The quasi-steady Nusselt number for a drop of condensate is calculated for an arbitrary contact angle in the range $(0, \pi/2)$ using a spherical segment geometry [41J]. One of the promising means of attaining dropwise condensation is to periodically introduce the required quantity of water-repellent into the stream [17J]. A new model is proposed (and the corresponding algorithm developed) to describe the temperature field of a suddenly exposed droplet experiencing moisture condensation from an air-stream mixture [27J, 59J]. Other experiments on direct contact condensation of steam bubbles in water at high pressure [2J] show that the successive shapes of the bubbles during their collapse histories proceeded from a sphere to a hemisphere to an ellipsoid to a sphere to collapse; short-lived bubbles collapse as ellipsoids. McCoy and Hanratty [29J] critically examine measurements of the rate of disposition of droplets in annular two-phase flow.

Two-phase flow

The frost formation process was studied by photographic observations [15J] and frost formation types and thermal properties were classified into several groups according to their structures in the temperature range of 0 to $-25°C$. Data are reported [46J] for flashing expansion flowrate and pressure profiles in convergent–divergent nozzles fed with high pressure subcooled water. Thirty micron glass particles increased turbulent thermal entry lengths and fully developed Nusselt numbers whereas 62 and 200 μm particles did not [55J]. Heat and mass transfer in rising two-phase flows in rectangular channels [23J] and tubes [10J] are described. Transient boiling flow instabilities in a multi-channel upflow system received attention [21J]. Heat transfer during cooling of the inner surface of a brass cap with boiling liquid nitrogen [25J] is described. Eighteen two-phase friction pressure drop models and correlations were tested against 2220 measured values under adiabatic conditions and 1230 diabatic conditions [9J]. The Baroczy correlation, the Thom correlation, and the homogeneous model multipliers gave "best" performances. A critical review is given [19J] of transient and statistical measurement techniques for two-phase flows.

RADIATION

Radiation in participating media

Radiative transport in emitting, absorbing and scattering gray and non-gray media, including in particle suspensions is still of considerable interest. There is a substantial increase of the research activities associated with thin films.

A mathematical relation is presented for the gas-to-surface radiative exchange area for a rectangular parallelpiped gas volume and an adjacent face [10K]. The generalized zone method is used for numerical calculation of the radiative heat exchange in a system consisting of a long square duct filled with an absorbing medium [39K]. The governing equations are derived for flows of a radiating gas at velocities close to the isentropic and isothermal speeds of sound in channels with slowly changing temperature and curved walls. This nonlinear system of equations defines the flow of gas in channels whose transverse optical thickness is of the order of unity [3K].

A method based on integral Fourier transform technique is used for obtaining both the total and the angular radiation intensity in a non-conservative, isotropically scattering, finite slab with an internal source and with general transparent boundary conditions [12K]. In preliminary studies the expansion of the simple one-dimensional, single scattering model is reported into a two-dimensional, multiple scattering model [29K]. The exponential kernal approximation is used to develop a closed-form expression which describes the apparent directional and hemispherical emittances as a function of the optical thickness, substrate reflectance and emittance, and scattering albedo of an isothermal, isotropically scattering medium [6K]. The influence of substrate reflectance on the radiative intensity and flux distribution and on the apparent reflectance and transmittance of an isothermal, isotropically scattering medium is examined by using an exponential kernal approximation to obtain a simple algebraic expression from which the bidirectional, directional hemispherical, hemispherical directional, and hemispherical reflectances can be evaluated [7K]. An "effective absorptivity in the presence of scattering" is introduced for the solution of the radiative heat-transfer equations through absorbing, emitting and scattering media. Comparisons of this method with results calculated with conventional methods shows that it is accurate and faster than present techniques [21K].

The principal advantages and disadvantages are discussed of modeling radiation heat transfer in participating media by means of a visible-light model [1K]. In a radiative fluid, the Doppler effect due to differential motions of neighbouring fluid elements causes photon mean-free paths to deviate from the static values. The radiative flux becomes in this situation a tensorial property [16K].

Studies of the interaction of radiative transfer with convective transfer for slug flow of an absorbing–emitting gas in a circular tube with an isothermal black wall demonstrate that inclusion of radiative transfer influences the gas temperature distribution for the conditions treated [31K]. Studies of the non-steady thermal response of a one-dimensional transpiration cooled system in a radiative and convective environment indicate that the surface solid and fluid temperature and the back-face heat transfer quickly respond to the incident pulse [25K]. Transient combined laminar free convection and radiation is considered in a rectangular enclosure containing a fire or other high temperature heat sources. Solutions of the conservation equations indicate that radiation dominates the heat transfer in the enclosure and alters the convective flow pattern significantly [26K].

Investigations of the applicability of the Milne–Eddington approximation for radiation heat transfer in combustion systems reveal that this approximation applies well to hydrocarbon soot particles. For the calculation of total band radiation from gases, however, this approximation appears questionable [18K]. Studies of the radiative-convective interaction in a laminar methane-air diffusion flame revealed excellent agreement between results based on the non-gray wide-band model and experimental data [32K]. Predictions of the homogeneous gray model are in reasonable agreement with spectral measurements of the radiance and transmittance of radiating flames with polystyrene, Delrin and Plexiglas as fuels [14K]. Studies of the effect of molecular gas radiation on a planar, two-dimensional, turbulent-jet-diffusion flame indicate that realistic non-gray radiation transfer analysis can be coupled to an implicit numerical method for solution of the coupled, highly nonlinear conservation equations without undue expenditure of computation time [17K].

Local nonsimilarity techniques are employed to analyze radiation–convection interaction in a liquid in natural convection flow adjacent to a vertical surface with constant wall heat flux. Solutions are in reasonable agreement with available data [8K]. Although studies of the IR spectrum of water as a function of temperature provide significant information regarding the water structure, no sudden spectral changes have been found at 30°C or at any other temperature in the range from 1 to 50°C [35K]. Using adiabatic laser calorimetric techniques the absorption coefficient of pure water is found to be 1.7×10^{-4} cm^{-1} at 488 nm and 2.9×10^{-4} cm^{-1} at 541.5 nm. The values are in good agreement with the generally accepted long-path transmission spectra of Clarke and James [22K]. Measurements of the optical constants of liquid H_2O and D_2O are now possible over a greatly extended frequency range from 6 to 450 cm^{-1} [2K].

Investigations of the spectral absorption characteristics of water vapor and carbon dioxide mixtures in the 2.7 μm band show that spectral distributions, predicted from published data for spectral H_2O and CO_2 absorption coefficients and the line half-width to spacing ratios, are in good agreement with measured distributions [36K]. A generalized direct exchange factor is derived for the analysis of radiative heat transfer in isothermal, molecular gases. These exchange factors are valid for any molecular-gas band absorption model [33K]. Measurements of the IR emission of the 4.5 μm combination band of nitrous oxide are reported for temperatures of 1200, 1700 and 1900 K, a temperature range for which no previous data are available [34K].

Light scattering and absorption measurements by opaque particles on a per unit mass basis indicate that the most efficient light scattering and absorption occur in the size range where the particle changes from a Rayleigh to a Mie scatterer [17K]. A mathematical description is given of combined radiative and convective heat transfer to and from a turbulent gas-suspension flow. Experiments indicate that with increasing wall temperature at constant solid loading ratio, Nu increases due to the rising contribution of radiative transfer [38K]. Measurements of the visible and near IR imaginary refractive index of size fractioned atmospheric dust samples show that this index can vary with particle size nearly two orders of magnitude at some fixed wavelengths [27K]. Imaginary refractive indices are measured in atmospheric dust in the 2.0–3.0 μm spectral range using a modified Cary 171 spectrophotometer [19K].

A method is described which allows the determination of the optical constants of thin films from measurements of normal incidence, reflectance, and transmittance even in regions near the critical points where successive approximations become very inaccurate [13K]. In connection with the optical characterization of thin films, a computer inversion method is used to show that a thin inhomogenous film can usually be approximated by one homogenous film [4K]. The minimum thickness of a metallic film for infrared reflectors is calculated and the reason why metallic films cannot be used for making Fabry–Perot filters in the IR is shown [15K]. The optical properties of single-layer gradient refractive-index films offer considerable advantage over conventional interference films in many applications [30K]. A high degree of spectral selectivity can be achieved with absorptive thin films of titanium or zirconium compounds on a reflective silver film. Solar absorptance in the range from 0.8 to 0.88 can be obtained while achieving low thermal emittances from 0.04 to 0.084 at 327°C [11K].

A simple method for calculating the absorptance, reflectance (R), and phase disortion of multilayer-dielectric reflectors is based on the zeroth-order ($R = 1$) electric field distribution in the coating [37K]. Linear programming is used for the design of antireflection coatings [35K]. There is a considerable increase in surface reflectance (approximately 9 times) and a drop in transmittance (46%) if there is dropwise condensation of the H_2O on the glass surface of a solar collector system [23K].

Laboratory measurements of radiative heating in ice are generally in agreement with the prediction of an analytical model which includes the effects of anisotropic scattering as well as the spectral dependence of the absorption coefficient of ice [20K]. A radiation probe is used for studying radiant heat transfer at the exit surface of a furnace which is part of a 300 MW steam generator [5K].

The spectral radiant intensity of burning jet fuel (JP-4) is measured in the spectral region from 200 nm to 18 μm and simulated altitudes ranging from sea level to 10.7 km. An extremely intense CO_2 emission band at 4.4 μm is of primary interest for possible use in connection with fire detection [28K].

SURFACE RADIATION

Three papers [2L, 7L, 8L] report emissivities of copper, aluminium, and silver at temperatures between 150 and 1000 K measured by a transient calorimetric method. Some values at high temperature deviate from theoretical predictions and previous measurements. The optical constants n and k were measured for gold film evaporated onto a base metal by transmission interferometry [5L]. The parameter n was found to decrease with λ in the range 4000–5000 Å from 1.50 to 0.2, whereas k increases from 2 to 4 cm^{-1} in good agreement with previous work. The same constants were measured [11L] for copper and nickel at 5461 and 6328 Å after cleaning the surface by ion bombardment. Ellipsometry (the study of surfaces by analysis of polarization of reflected light), was used [3L] to study the optical constants of selective surfaces.

The effect of large pyramidal surface roughness on spectral directional emittance was calculated [1L] for a ratio of roughness height to wave length much larger than one (applying geometric optics).

Local temperatures in semi-gray, non-diffuse cones and V-grooves, calculated [9L] with radiosity integral equations, were found sensitive to higher order interreflections near the apex. Equivalent emissivities describing radiative heat transfer in three and four row systems of gray cylinders were calculated [4L]. Diagrams present [6L] shape factors for radiative energy transfer between rings and inverted cones sharing a common axis. A synoptics presents an analysis [10L] of thermal radiation effects on a normal shock wave incident on a plane wall.

LIQUID METALS

A simple model of the movement of an inert gas bubble in a liquid metal describes very well the actual behaviour [3M]. The analysis should be useful for design studies of the liquid-metal fast-breeder reactor. Experiments [1M] showed that a bubble moving in mercury changes shape from spherical to elliptical to spherical cup as the radius changes from 0.1 to 3 mm. A magnetic field generally decreases the rise velocity.

The results of heat-transfer measurements [2M] during the dropwise condensation of mercury agree well with previous studies.

MEASUREMENT TECHNIQUES

The development of instrumentation related to heat-transfer studies continues to draw the attention of a number of investigators. Areas of primary interest include temperature and heat flux measurement, radiation property evaluation, hot wire anemometry, and laser-Doppler anemometry. In addition, special instrumentation has been described for measuring quantities such as thermal diffusivity, wall shear and void fraction.

Differences in the thermal history of low-temperature glass-ceramic capacitance thermometers result in irreproducibilities in their equilibrium calibrations [43P]. An apparatus has been developed for thermal cycling germanium thermometers and evaluating their reproducibility at approximately 20K [37P]. A method of the remote measurement of temperature fields of bodies, within approximately 0.2 C in the −30–200 C range, is based on the detection of their infrared radiation with subsequent transformation of that radiation into electric signals which are displayed on a CR tube [14P]. An inexpensive recording thermometer has been developed which is accurate to ±0.4 C in the 0–30 C temperature range [27P].

The temperature distortion caused by a cavity drilled into a disk to accommodate a thermocouple can be eliminated by a properly chosen combination of the ratio of thermocouple diameter to cavity diameter and the thermocouple material [10P]. Voltage spikes generated across a 12-cm length of alumel wire in a 60 Hz sinusoidal magnetic field with an intensity of 200 A/m have been observed which would correspond to an instantaneous temperature error of 35 C if the wire were one leg of a chromel–alumel thermocouple [34P]. This effect was further demonstrated in tests which showed that chromel alumel thermocouples used in a magnetic field indicated temperatures in error by about ±150% at 100 C [29P]. A mechanically pulsed suction thermocouple has been developed and has proved to be a reliable and fast tool for the measurement of local gas temperatures within the combustor of an aircraft gas turbine [30P].

A number of unique temperature measuring devices have been described. Two types of surface thermometers, produced using micro-electronic thin film technology, have been successfully applied to the difficult experimental task of measuring surface temperatures during high conductance processes such as condensation and boiling [20P]. Thin films of collodial graphite applied as an aerosol spray, which is commercially available, were tested for use as thermometers and exhibited good stability at low temperatures but were affected by humidity at room temperature [13P]. Analytical and experimental investigations predict that fluidic capillary temperature sensors could be developed which would have resolution capabilities of

0.001°C [15P]. A method for determining temperatures of solid particles from changes in their magnetic properties can be employed for tracing the motion of a single particle in a fluidized bed [2P]. A new technique, based on rotational Raman scattering, has been described for simultaneously measuring temperature and concentration profiles in diatomic gases during transient flows [40P]. A sensible heat flux detector has been evaluated [12P].

A relatively simple experimental procedure can be used to determine the temperature dependence of the response of instrumentation used to measure radiation, thus minimizing the errors incurred when such measurements are performed in the field or other uncontrolled temperature environments [31P]. The absorption of infrared radiation in thin film coatings can be determined by the separation of surface and bulk absorption using laser calorimetric measurements [21P]. Transmission, emittance, and calorimetric techniques of measuring the absorption of materials are described, with special emphasis on how calorimetry can be used to simultaneously determine bulk and surface absorption [24P]. A system is described which makes it possible to measure the spectral reflectance of materials in the 0.3–2 μm wavelength range for a hydrostatic pressure range of 0–70 kbar [46P]. In an attempt to improve the accuracy of reflectance determinations of high vapor pressure liquids, a double ionization chamber has been built and tested which measures the ionization from a photon beam in the vapor (or an added gas) above the liquid before and after reflection [6P].

The evaluation, calibration and application of hot-wire anemometers was the topic of several papers. The calibration and use of hot-wire probes in low density flows was discussed [18P]. Experimental studies are reported on hot-wire anemometers with wires of short relative lengths (L/D varying from 300 to 540) for use in low velocity streams and a simple iterative procedure is proposed for determining true velocities from the probe readings [41P]. Frequency response measurements show, contrary to presently used theoretical models, that for wires with substantial end conduction losses, a single time constant response is not obtained [8P]. The heat transfer from cylindrical anemometer probes in CO_2 air mixtures has been studied [9P]. Modified sets of response equations have been derived for an inclined hot-wire probe which permit the determination of the components of the three dimensional velocity vectors, the turbulence intensity, and the Reynolds stresses at any location of a swirling flow [4P]. For the application of hot-wire anemometry in transonic flow, it has been established that (for a sensor Reynolds number greater than 20 and high sensor overheat ratios) the velocity sensitivity remains independent of Mach number and is equal to the density sensitivity [25P]. The application of a dual hot-wire temperature sensing technique to transient, supersaturated gas flows facilitates previously impossible quantitative observations of deviations from ideality of supersaturated gases [17P].

The theory and the application of the laser-Doppler anemometers (LDA) continue to be areas of interest. The signal visibility characteristics of a dual beam LDA operated in a backscatter mode depends on the Mie scattering size parameter, the refractive index, the beam polarization and the size, shape and location of the light collecting aperture [1P]. Measured correlations of scattering powers and signal-to-noise ratio as function of angle for an LDA are generally in excellent agreement with Mie theory [3P]. Errors which occur when using LDA within turbulent phase boundaries (e.g. turbulent flames) have been analyzed and experimental techniques to minimize such errors have been proposed [23P]. Coherent differential Doppler measurements of a transverse velocity at a remote point have been investigated [39P].

A dual-plate holographic interferometer is purported to have several advantages over the traditional single-plate dual-exposure apparatus including insensitivity to mechanical vibration, availability of Schlieren and shadowgraph images from the same holograms, and the ability to arbitrarily position the fringes during reconstruction [19P]. Holographic measurements offer a means to investigate the fundamental structure of boundary-layer turbulence and transition for hypersonic, high Reynolds number flow around various shaped bodies at both zero and small angles of attack [22P].

Special instrumentation has been applied to boiling studies. A rotating-field conductance gauge provides a useful and versatile, yet relatively simple, technique for measuring void fractions [35P]. The application of nuclear magnetic resonance [NMR] to the measurement of void fractions of two-phase flows has also been studied. Experiments on both static and flow systems have established the linearity of the NMR method for the full range of void fractions and have demonstrated the feasibility of directly using the NMR method for measuring void-fractions [33P]. An investigation of two methods of detecting boiling crisis on a non-isothermal surface, resistance bridge and thermocouple, indicates that the bridge approach is more reliable since it responds faster and responds to crisis onset at any point [28P].

A porous plate floating element was used to accurately measure the shear stress in a transpired zero pressure gradient boundary layer in the range from laminar asymptotic suction to blow-off [11P]. Wall shear stress measurements can be made in a variable temperature flow field with a hot-film probe which has been calibrated to account for flow temperature changes [38P].

A limited number of papers. describe the measurements of transport properties. A thermal diffusivity apparatus can perform measurements in transient and periodic temperature modes on electrically conducting solids which have medium range thermal diffusivities [36P]. A comprehensive method exists for measuring the specific heat and thermal diffusivity of liquid and free-flowing materials [16P]. A modification of the transient hot-wire method of measuring thermal conductivities provides a simplified means for obtaining engineering data of moderate precision and accuracy [45P].

English-language translations of Russian papers dealing with the following topics appeared in Measurement Techniques: (a) ultrasonic resonance methods of temperature measurement [42P]; (b) apparatus for studying and calibrating resistance thermometers, thermodiodes and thermocouples [5P, 32P, 44P]; (c) the effects of thermoelectric nonuniformity of electrodes on differential thermocouples [7P]; and (d) the determination of the convective heat-transfer coefficient from a gas to a thermocouple [26P].

HEAT TRANSFER APPLICATIONS

Heat exchangers and heat pipes

The utility of the use of heat- and mass-transfer coefficients is investigated in [19Q]. It is concluded that in general the use of such coefficients offers advantages in design calculations. There are, however, exceptions where the analyses become simpler if based on heat flux.

Experiments demonstrated [8Q] that oblique flow and an intermediate tube arrangement cause a decrease in the material required for a heat exchanger by approximately 10%. Local heat-transfer coefficients and pressures around the circumference of a tube at various locations in a tube bundle were measured [24Q] at Reynolds numbers from 6×10^4 to 1.7×10^6 and at Prandtl numbers between 3 and 6. The large variations (56%) occurring in the first row of the bundle decrease to 27% in the fourth row. A method [13Q] to calculate heat transfer in tube bundles with external longitudinal fins affected by heat conduction in the fins is presented. The effects of non-uniform passages on the performance of plate fin heat exchangers were statistically modeled [16Q]. Results agree well with measurements. The deposition of paraffin wax from kerosene in cooled heat exchanger tubes generates a heat-transfer resistance which fluctuates in time after a short initial period [3Q].

The performance of cross-flow heat exchangers with variable physical properties was calculated [23Q] based on the assumption that the heat-transfer coefficient varies according to a power law with distance or temperature. The results indicate that conventional methods are not accurate for large exponents in the power law. A short note [7Q] presents a relation for the mean temperature difference in odd-tube-pass heat exchangers. A new rotary plate evaporator was described [18Q] where the evaporation occurs from a thin film carried by the rotation along the heat exchangers surface. A heat exchanger design method [1Q] makes it possible to design for prescribed or minimum entropy production.

Two papers [11Q, 22Q] present analyses of regenerators in which condensation occurs, based on the assumption of local thermodynamic equilibrium. The results of an investigation [2Q] of heat transfer to spiral coils during the mixing of a non-Newtonian liquid by anchor mixers are presented as a function of Re, Pr, μ/μ_0 in a Reynolds number range from 21 to 28 200, for Prandtl numbers between 19.2 and 8.264, and an exponent in the shear deformation relation between 0.65 and 0.87.

Mathematical models [6Q, 9Q] are offered for the calculation of spray cooling systems. The Ranz–Marshall correlation serving the same purpose was found [5Q] to agree within ±5% with experiments on droplet temperatures.

Three papers [4Q, 12Q, 17Q] offer methods for the synthesis of heat exchanger networks. Design considerations are discussed [15Q] for heat exchangers in a gas turbine power plant. The temperature distribution in a cooled radial in-flow turbine rotor is reported in [10Q].

An efficient numerical method for the analysis of nuclear reactor cores was developed [14Q] and integrated into the COBRA-IIIC Code. Measured values for natural circulation in an experimental sodium cooled breeder reactor [20Q] agreed well with predictions of an analytical model. Fluctuations were detected [21Q] in the tubes of a large capacity, straight-tube, once-through sodium heated steam generator with a frequency depending on transit time, Froude number, and the ratio of the length of the boiling region to the total heated length.

AIRCRAFT AND SPACE VEHICLES

Ablation and thermal protection systems, in particular for space shuttle applications are still of considerable interest.

There have been a number of technological uncertainties concerning the applicability of radiative, metallic thermal protection systems (TPS) to the multimission environment of the space shuttle [3R]. A broad-based technology program at NASA Langley demonstrates that metallic TPS are competitive with those for shuttle reusable surface insulation. Numerical computations of flow fields and laminar heating rates around the Space Shuttle orbiter windward surface, including the root of the wing leading edge, illustrate the sensitivity of these calculations to several flow field modeling assumptions [4R]. In a similar study exact inviscid flow field codes are used, together with a quasi-three dimensional boundary-layer analysis to estimate windward surface heating and streamline patterns of the shuttle orbiter vehicle under laminar flow conditions [10R]. Studies of re-entry vehicle stagnation region heat transfer in particle environments indicate that heating augmentation is dominated by surface roughness effects. This roughness is due to surface erosion caused by impinging particles [7R]. The effects of sealed heatshield tile misalignment producing "roughness elements" have been studied with respect to orbiter boundary-layer transition [5R]. Wind-tunnel results indicate that the effects of roughness on the location of boundary-layer transition for the orbiter is strongly affected by the ratio of wall to total temperature.

No definite conclusions can be drawn from comparisons of wind-tunnel and flight test heat-transfer measurements on pylon-mounted stores because of the scatter of the flight test data [9R]. Studies of ablation effects under laminar flow conditions in a wind-tunnel simulation facility at $M = 10$ on a sharp 5° half angle cone indicate that care must be taken in fabricating porous mass-injection models because the mass-injection distribution can have an effect on the measured stability or drag [6R]. Transient ablation studies of Teflon hemispheres show that the effect of thermal expansion is significant and that the internal temperature distribution changes abruptly in a very thin layer near the body surface [1R]. Reliable predictions of high heating rate pyrolysis phenomena cannot be made from data obtained in conventional low heating rate apparatus based upon our present understanding of the pyrolysis process [2R].

Coating systems consisting of plasma-sprayed layers of zirconia stabilized with either yttria, magnesia, or calcia over a thin alloy bond coat have been investigated as thermal barrier coatings for cooled turbines [8R]. On the basis of durability and processing cost, the yttria-stabilized zirconia is considered to be superior. Electroless metallic plating techniques have been used for making advanced models for aeroheating tests. Mach 7 test results using several simple models demonstrate that this plated slab approach provides valid aeroheating data [11R].

In order to provide simple engineering approaches for predicting turbulent boundary-layer heating, data obtained in both ground and flight tests are compared with results from several prediction methods in the respective incompressible planes [12R].

GENERAL

A number of papers with numerous contributions from the Soviet Union deal with heat and mass transfer in the ground. Analyses on the effect of permafrost are presented [4S, 5S, 22S] and compared with experiments. Experimental data are available on the effect of snow cover [3S]. A computer program [8S] considers unsteady nonlinear heat conduction in pavement structures. The results are compared with experimental findings in Norway. Polymeric films are considered [16S] for artificial soil thawing. An analysis [18S] of transient heat and mass transfer in soils close to heated porous pipes accounts for liquid and vapor transport. Seasonal soil temperatures for three climates are presented.

Analyses [1S, 2S, 21S] study geothermal energy extraction by fracturing of rocks. An emprical correlation of experimental data [12S] describes the relation of grassland surface temperature and air temperature.

A number of papers deals with heat transfer in homes. It is found [17S] that the pitch of the roof should be around 15° to achieve optimum insulation effect. The results of an analysis [9S] describing the temperature change between air inlet and outlet of a room agree well with experiments on a two-dimensional model. A mathematical model [20S] predicts multilayer chimney-liner temperatures for unsteady state. A compressive mechanical load reduces the heat-transfer resistance of clothing fabrics considerably [15S]. Experiments [11S] established heat absorption rates of a sprinkler spray used to cool room fires.

Thermal resistance of metal/diamond interfaces used at microwave diodes was measured [6S] at 400K. Prestressing decreases the thermal contact resistance of laminated transformer stacks [14S]. Surface temperatures in sliding contacts were studied analytically [7S] by a Fourier transform method and experimentally [13S] by an infrared technique. Correlations [19S] predict quenching rates and sputtering temperatures for rewetted nuclear fuel elements. An analysis [10S] of submerged multiple port discharges is based on a gradual transition of the jets from axisymmetric to merging to pseudo-slot two-dimensional profiles and the results are compared with experimental findings.

SOLAR ENERGY

Solar energy continues to be an active applications area. Topics of major interest among the heat-transfer related solar energy publications include solar flux, flat plate collectors, concentrating collectors, solar absorber coatings, and thermal energy storage.

Methods of estimating the average daily solar radiation incident on a surface have been reviewed and the methods extended to allow predictions to be made for a wider range of surface orientation [11T]. Experimental results have been used to modify and improve a model for predicting the flux of solar radiation incident on a sloping surface [29T]. Instrumentation has been developed which has the accuracy and precision needed to determine the spectral distribution of daylight at any geographical location such that comparisons between various locations can be made with uncertainties of less than 2% [12T].

In many applications, a portion of the total solar flux incident on a collector is energy which has been reflected from the ground. The average solar reflectivity of winter landscapes varies from as low as 0.16 in areas containing open water to as high as 0.73 in typical rural areas [9T].

The performance analysis of flat plate collectors was the subject of several publications. A steady-state, two-dimensional, nodal, heat-transfer analysis was used to demonstrate that operating a collector with constant outlet temperature can be as efficient as operating with a constant mass flow rate [24T]. The same model was used to establish that long term flat plate collector performance calculations based on averaged meteorological data will only correlate with calculations based on hourly data if the weather conditions are not highly variable [23T]. However, in the case where weather conditions are not varying rapidly, the use of an integrated collector equation makes the calculation of monthly and annual solar collector performance a simple task if the average collector temperature is known [7T, 13T]. Another two-dimensional steady-state model of flat plate solar collectors was used to evaluate the sensitivity of collector performance to changes in design parameters

[19T]. A flat plate collector analysis, suitable for a programmable desk calculator, was used to predict that the reduction of radiation losses which can be achieved by the application of low emittance coatings for the absorber plate results in an increase in the convection losses [30T]. The mass flow rate and temperature distribution in a natural-circulation solar water heater were evaluated using both linear and non-linear temperature distribution models with the result that the flow rates predicted by the two models differ by less than 10% [31T].

Performance measurements demonstrated that a single-glazed flat-plate solar collector with a glass honeycomb mounted between the absorber plate and the cover glass is capable of operating at efficiencies as high as 55% with the working fluid 65 C above the ambient temperature [14T].

Two of the fundamental heat-transfer processes which occur in flat-plate solar collectors have been examined in deeper detail than in the past. Experimental studies of forced convection heat transfer at an inclined and yawed square plate demonstrated that the standard computational equation substantially over estimates the wind related heat-transfer coefficient on the outer surface of a flat-plate solar collector [27T]. An analysis of the heat-transfer processes in a solar collector tube revealed that for realistic dimensions and thermal properties of the plate and tube, circumferential variations of the ouside temperature and bore heat flux can be neglected, provided the tube flow is laminar [26T].

Analytical and experimental studies dealing with concentrating solar collectors have been reported. The optimum concentration ratio for a solar collector has been shown to be a function of a dimensionless temperature (receiver temperature/ambient temperature) and a dimensionless receiver number which is proportional to the ratio of the receiver heat loss to the absorbed fraction of the solar insolation [2T]. The results of a closed form analysis of the solar flux distributions produced on the surface of a central tower receiver are presented in the form of universal curves which can be used readily to study the effects of changes in system parameters [21T]. A study of different designs of central tower. air heating receivers has shown that high thermal conversion efficiencies (80–90%) may be achieved with cavity receivers while substantially lower efficiences (54–70%) were predicted for exposed surface receiver designs [10T]. A cylindrical parabolic solar collector was shown experimentally to be capable of achieving thermal efficiencies of 50 and 30% respectively for selectively coated and black painted absorber tubes while operating at a temperature of 300 C [18T].

The use of selective coatings which have high solar absorptance and low infrared (IR) emittance is an effective means of improving the thermal efficiency of solar collectors. A survey of selective absorber coatings for solar energy technology describes both the past accomplishments and promising new materials [15T]. A coating with a solar absorptance as high as 92% and an IR emittance as low as 3% has been produced by electroplating black-chrome onto a copper substrate [6T]. A model which treats the black-chrome of this type of coating as a collection of small particles, either as metal in a dielectric or dielectric particles within the metal, is capable of predicting the range of observed radiation properties, especially the variations in the IR emittance [8T]. The solar transmittance of a gold black film has been shown to depend on the gold particle size and packing fraction in the film [17T]. A five parameter empirical Fermi function can be used to describe the spectral radiation properties of selective solar absorber coatings and the model predicts that the IR emittance of typical coatings will increase with temperature at the rate of approximately 2–5×10^{-4} emittance units/ C [25T]. The optical constants of silicon single crystals and sputtered amorphous silicon films at temperatures up to 800 C have been determined and, based on these values, the solar-thermal efficiencies of silicon–metal selective absorbers have been predicted to be as high as 79% at 400 C [1T].

There was a significant increase in the number of energy storage publications. The majority of these described sensible energy storage systems. The development of closed-form solutions for the transient response of a packed bed provides a simple and convenient means for estimating the long-term dynamic performance of rock-bed thermal storage systems [20T]. A technique, suitable for the optimization of the design of a solid sensible heat storage unit, can be used to establish possible operating ranges for the fraction of the maximum heat stored and the fraction of the available energy stored at a given set of conditions and system constraints [22T]. An analysis of unsteady heat conduction in a composite hollow cylinder with the heat source at the inner surface of the cylinder revealed that the thermophysical properties of each layer of the composite affect the temperature distribution, rate of temperature increase, and the amount of heat stored in the material [28T]. The temperature profiles and streamlines in a liquid filled thermal energy storage tank can be predicted with a two-dimensional model and the temperature profile along the vertical axis of the tank can be predicted to within approximately 15% using a simplified one-dimensional analysis [4T].

A preliminary guide, including several monograms, has been developed to aid the designer in the assessment of sensible and latent heat storage systems for both short and long term applications [16T]. Initial tests of a latent heat storage concept indicate that the major problem preventing the use of sodium sulfate decahydrate (i.e. the degradation of capacity with cycling) can be avoided by using a mixture of 68.2 wt% $NaSO_4$-$10H_2O$ and 31.8 wr% H_2O [3T].

A proposed system which uses adsorbent beds for energy storage has a much higher stored energy density than non-adsorbent systems, requires no thermal insulation and has an indefinite storage period [5T].

PLASMA HEAT TRANSFER

Heat-transfer studies in ionized gases reported in 1977 refer to fundamental investigations as well as to applications, in particular to those using electric arcs or rf-discharges as a heat source.

High speed photographs of the luminous core of an AC arc in an orifice air flow demonstrate that the luminous core area can be correlated by a parameter which is derived from the enthalpy flow, the kinetic energy transport, and an empirical radiation term [20U]. Temperature measurements in AC cross-flow arcs of 61.1 A RMS shows that the temperature reaches a minimum after current zero [21U]. In magnetic-blast circuit breakers the current distribution over the cross section of a narrow insulating slot may cause thermal overload of the arc chamber. Results of pertinent studies show that the current density is higher on the arc "front" and lower on the "tail" [18U]. Results of a numerical simulation of a decaying air plasma column show a non-exponential decay of the temperature at the axis in the beginning caused by pressure oscillations. The overall decay is exponential and agrees well with experimental results [10U].

A free-burning high intensity, pulsed arc ($I < 23$ kA, $t = 10$ ms) in air on steel cathodes changes from a convection ($t < 3$ ms) to a radiation dominated regime (3 ms $< t <$ 6 ms). For $t >$ 6 ms, the arc becomes unstable which is probably associated with diminishing cathode jet convection [17U]. Time-dependent plasma temperature measurements in a 60 Hz high-pressure sodium arc correlate well with the steady-state and time-dependent plasma characteristics calculated from arc dimensions, power density, thermal conductivity, radiative heat transfer, and other arc parameters [16U].

Threshold current densities which are associated with the corresponding threshold heat fluxes leading to the formation of anode spots are studied for Al and Cu anodes in triggered vacuum gaps. They are found to depend upon the duration of arcing time, on the electrode material, surface conditions, electrode size and separation [8U]. An energy balance at the arc root of a Cu-cathode covered with a thin film indicates that Joule heating is more important than positive ion bombardment which confirms a filamentary switching model [7U].

Measurements of the continuum emission coefficient in a wall-stabilized argon arc in the range from 2 600 to 7000 Å at pressures from 1 to 30 atm and temperatures from 11 200 to 13 200 K show discrepancies with theoretical predictions. These discrepancies at high pressures cannot be entirely explained by a shift of recombination thresholds [3U]. Spectrometric studies of the boundary layer in front of a plane anode perpendicular to the axis of a wall-stabilized, high-intensity arc in argon atmosphere indicate substantial deviations from LTE [6U]. Calculated transport coefficients of a two-temperature argon plasma are presented for electron temperatures ranging from 5 000 to 20 000 K using electron temperature to heavy particle temperature ratios from 1 to 3 and pressures from 10^{-3} to 10^3 atm [9U]. Plasmas heated uniformly by inverse bremsstrahlung approach a constant electron–ion temperature difference which is only a function of the laser wavelength and intensity [15U].

Studies of the radiative energy loss from an argon plasma in a shock tube show that for the primary shock, emissivity effects outweigh reabsorption, whereas for the reflected shock region, the relative influence of reabsorption increased sufficiently to reduce radiation cooling of the plasma [11U]. Atomic and ionic temperatures in argon and helium plasma jets are derived from laser-Doppler measurements of the flow velocity coupled with dynamic and static pressure measurements [4U].

With specialized instrumentation, the problems experienced during actual welding operations, such as arc fluctuations induced by the moving weld pool, can be overcome and useful determinations made of the heat flow geometry within the arc [14U]. In electro-discharge machining removal of material is due to melting and evaporation of the metal. For a given heat input and a maximum surface temperature, the center depth and the radius of the heat source are correlated by a universal function [12U].

A survey on plasma technology and its application to extractive metallurgy stresses the potential of plasma furnaces for metallurgical processing, in particular the use of plasma heating for the production of ferro-alloys [5U]. When mixtures of WO_3 and TiO_2, ZrO_2, or HfO_2 are heated with graphite in an argon plasma arc furnace, cubic solid solutions in the W–Ti–C, W–Zr–C or W–Hf–C systems are formed which turn out to be superconductors. Their transition temperature varies with composition [13U]. Numerical predictions of the behaviour of iron particles with radii from 20 to 80 μm injected into an rf-plasma indicate that particles with radii less than 70 μm will melt under the chosen plasma conditions. Previous models seem to overestimate this potential of rf-plasmas for powder processing [22U]. Graphite materials exposed to arc-heated jets at stagnation pressures from 2.2 to 10.3 MPa and bulk enthalpies from 4700 to 5800 kJ/kg reveal non-uniform surface ablation which can be correlated with porosity, fiber density, and the fiber-matrix interfacial spacing [1U].

Studies of the design of a closed-cycle MHD generator employing nonequilibrium ionization and of the overall performance of a power plant which uses a MHD topper for a steam bottoming plant demonstrate the feasibility and adaptability of the analysis for optimizing the thermal efficiency [19U]. Investigations of the Hall effect on the combined free and forced convection, full-developed flow in a parallel plate channel with perfectly conducting walls reveal that the heat transfer at both plates decreases with increasing Grashof number and increasing Hall parameter [2U].

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