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HEAT TRANSFER—A REVIEW OF 1976 LITERATURE

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INTRODUCTION

THIS review surveys results that have been published in various fields of heat transfer during 1976. 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 Sixteenth National Heat Transfer Conference was held 8–11 August 1976 in St. Louis, Missouri. The recipient of the Max Jakob Memorial Award, R. G. Deissler, presented an invited lecture, "Tornadoes and other atmospheric vortices". A lecture entitled "An inquiry of selected topics on heat-exchange design" was given by A. C. Mueller, who received the 1975 Donald Q. Kern Award. A third invited lecture on "Water reactor safety research programs" was presented by L. S. Tong. Twenty-eight sessions treated, among other subjects, interfacial phenomena, internal heat generation, process heat transfer, thermonuclear power, and heat transfer in foodstuffs. The papers presented at the conference are available as preprints and many of these will be published in the *Journal of Heat Transfer* or in the publication series of the American Institute of Chemical Engineers.

The 25th Heat Transfer and Fluid Mechanics Institute was held 21–23 June 1976 at the University of California, Davis, California. An invited lecture by P. Bradshaw discussed progress and problems in the development of turbulence models; another lecture by R. Davis treated numerical methods for interacting boundary layers. Five sessions were concerned with thermal convection, two-phase flow and boiling, compressible and turbulent flow, combustion, and aerospace heat transfer problems. Proceedings are available through Stanford University Press.

The Scientific Affairs Division of the North Atlantic Treaty Organization assembled a group of experts to review research needs on thermal energy storage and to make recommendations for future research. One of the panels discussed heat transfer and thermal energy transport. A report of the conference is available through the Scientific Affairs Division, North Atlantic Treaty Organization, Brussels, Belgium.

An International Solar Energy Conference was held 15–20 August 1976 at Winnipeg, Canada under the title "sharing the Sun 76". Many of the papers presented included heat-transfer problems.

An advanced course and the 1976 International Seminar were organized by the International Centre for Heat and Mass Transfer 23 August through 4 September 1976 at Dubrovnik, Yugoslavia. The summer course was entitled "Heat Disposal from Power Generation", and dealt primarily with cooling towers and climatic modifications by energy production. The seminar, "Turbulent buoyant convection", discussed plumes, stratified fluids, air and smoke movements in buildings, and combustion phenomena. The proceedings of these conferences will be published by Scripta Book Company, Washington, D.C.

The American Institute of Chemical Engineers focussed attention on plasma chemical processes in four sessions of its Eighty-Second National Meeting held 29 August through 1 September 1976 at Atlantic City, New Jersey, with heat-transfer information included in some of the papers. Other sessions dealt with transport processes in the oceans and with interfacial phenomena.

The 97th ASME Winter Annual Meeting, held 5–10 December 1976 at New York City, included in its program eleven sessions organized by the Heat Transfer Division. Topics ranged from application of computer technology through electric effects, liquid metal fast breeder reactors, thermal energy storage, pipe line heat transfer, heat exchangers, to solar collectors. Reprints of the papers are available from ASME Headquarters and many of them will also be published in the *Journal of Heat Transfer*. The dinner speaker, P. E. Glaser, talked on "The future of power from space". Heat Transfer Memorial Awards were presented to W. H. Giedt and R. Viskanta.

A number of books dealing with heat transfer or including heat-transfer topics have appeared on the market. They are listed in the bibliographic portion of this review. Volume 12 of the series, *Advances in Heat Transfer*, published by Academic Press, New York, became available in 1976. It contains contributions on dry cooling towers, heat transfer in flows with drag reduction, molecular gas band radiation, and a perceptive on electrochemical transport phenomena.

Developments in heat-transfer research during 1976 can be characterized by the following highlights: solid–liquid phase change, fins, and contact resistance found special attention in the area of heat conduction. A number of numerical solutions have also been reported. Flow and heat transfer in complex passages and solidification of liquids flowing through ducts were investigated. The entrance region of ducts was treated analytically for laminar flow, and various turbulence models were applied to the analysis of turbulent duct flow.

Impulsively started boundary layers were considered and detailed measurements and analyses in free and impinging jets were reported. Studies continue to be made on flow and heat transfer over cylinders with special attention to the near critical Reynolds number region. The number of papers on heat transfer in fluidized beds increased sharply. Measurements of the fluctuating velocities and temperatures, new models of turbulence and the application of kinetic and statistical theory attempted to improve our understanding of the turbulent transfer mechanism.

Many papers are concerned with natural convection, expecially in inclined fluid layers at low and moderate Rayleigh numbers, with non-Newtonian or micropolar fluids and with porous media. Flow and heat transfer in enclosures with partially rotating surfaces were investigated analytically and experimentally. Emphasis in the field of combined heat and mass transfer was on applications and on detailed local measurements. Surfaces which enhance boiling and condensation were developed for various engineering uses.

Attention was given to radiative heat transfer in non-gray media in combination with convection and conduction. Emissivities are reported for various surfaces and cavity shapes. Detailed measurements of the bubble growth clarified boiling heat transfer in liquid metals. Interest in plasma heat transfer shifted from aerospace to chemical and material processing applications. Electric arcs were used as a heat source. The laser-Doppler method and hot wire instruments were frequently used, and radiative transport and thermophysical properties were measured.

Heat exchangers found considerable attention with studies concentrating on local measurements by the use of the heat and mass transfer analogy and on more sophisticated computer analyses. Pollution in lakes and in the urban atmosphere, heat transfer in rock drilling, prevention of freeze-up of pipe lines, polymer moldings, reactor accidents, measurement of insolation parameters, flat plate and concentrating solar collectors, and energy storage found attention.

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

Conduction, A
Channel flow, B
Boundary-layer and external flows, C
Flow with separated regions, D
Transfer mechanisms, E
Natural convection, F
Convection from rotating surfaces, G
Combined heat and mass transfer, H
Change of phase, J
Radiation
  Radiation in participating media, K
  Surface radiation, L
Liquid metals, M
Measurement techniques, P
Heat-transfer applications
  Heat exchangers and heat pipes, Q
  Aircraft and space vehicles, R
  General, S
  Solar energy, T
Plasma heat-transfer, U

CONDUCTION

Problems involving phase change evoked considerable interest among recent papers on heat conduction. A substantial interest in fins, in thermal contact resistance, and in numerical solution methods is also reflected in the current literature.

For phase change problems, available analytical methods of solution, both exact and approximate, have been reviewed and a corresponding bibliography assembled [42A]. The enthalpy model, which had previously been applied only for cases with no density change, has been extended to accommodate substances which undergo a change of density upon phase change [53A]. Biot's variational method was successfully applied to yield a lengthy closed-form solution for a phase change problem with radiative heating [46A]. A Laplace transform solution of the Neuman phase change problem agreed well with the classical solution [25A]. A two-region moving boundary problem with conduction in one region and coupled conduction–mass diffusion in the other can be transformed into a Stefan-type problem with error-function solutions [41A]. The heat balance integral has been generalized to accommodate phase change problems with variable thermophysical properties [13A]. Phase change with variable properties was solved numerically by a two time-level implicit method in conjunction with Taylor's forward projection method [40A].

The analysis of solid–liquid phase change in a binary alloy requires that mass diffusion be considered along with heat conduction [8A]. In the analysis of transient ablation of a teflon layer, account is taken of crystalline-amorphous phase transition, thermal expansion, depolymerization, and formation of higher-molecular products [26A]. The most efficient power level for melt-through of a metal target due to laser heating minimizes the radial heat flow away from the melted region and does not vaporize the melt [61A]. In an investigation of salt redistribution phenomena during the freezing of a concentrated salt solution, it was found that the solute concentration increases with time [24A]. Simultaneous heat and mass transfer in the presence of a moving interface is also encountered in the freezing of foodstuffs [59A].

A Stefan-like problem in the *in vivo* freezing of a biological tissue took account of blood profusion, metabolic heat, and tissue heat capacity [49A], Thermal responses of biological systems undergoing freezing, as in cryosurgery, were determined through the application of the finite-element method [14A]. Other applications of the finite element method included frost heave of an embankment, ground freezing, and the stress distribution in a solidifying bar [35A]. A one-dimensional model of freezing and thawing ground with a seasonally varying surface cover was used to study the factors that produce differences between the yearly means of the air and ground temperatures [23A]. Transient heat transfer in a hot granular material being poured into a cylindrical container is a moving boundary problem which can be solved quasi-statically by letting the coordinate system move with the filling level [33A]. The final stages of freezing of an inward solidifying sphere have been described by an asymptotic theory for the case in which the ratio of the latent heat to the sensible heat is large [57A].

Fins continue to be an active applications area. In an optimization study of circumferential and longitudinal conducting–radiating fins based on maximizing heat transfer per unit weight, fins of triangular profile were found to be superior to those of rectangular profile [51A]. Use of an individually optimized fin profile does not necessarily result in an optimum multifinned surface [18A]. It has been proposed that the fin of infinite length serve as the basis of an alternative definition of the fin efficiency [6A]. The transient response of a fin has been evaluated for temperature variations in a fluid flowing adjacent to the back side of the wall to which the fins are attached [58A].

Variational techniques were used to find the fin shape which maximizes the heat loss for a given fin volume, with the added constraint that the fin thickness is bounded between upper and lower limits [3A]. A variational technique yielded fin efficiency results for simultaneous convective–radiative heat loss [9A]. When applied to a fin with a linear, temperature-dependent thermal conductivity, the Galerkin method provided fin efficiency results that agreed well with those from a numerical solution [43A]. An extension of the heat balance integral is made which encompasses steady two-dimensional heat-conduction problems where the conduction is almost one-dimensional, but for which the one-dimensional theory becomes unreliable [52A]. Upper and lower bounds on the temperature solutions for unsteady heat transfer in a fin-like rod were obtained in a mathematically oriented paper [11A].

Various aspects of thermal contact have been studied. The constriction resistance at an annular contact area supplying heat to a coaxial circular tube has been derived from heat conduction solutions [67A]. Insertion of interstitial plates between contacting surfaces is an effective means of decreasing thermal contact resistance [63A]. Analysis of the thermal contact between wavy surfaces shows a directional effect which is stronger at low applied pressures and high heat fluxes [20A]. The thermal contact conductances of lead ferrite and boron nitride exhibit a significant dependence on temperature and pressure, and increase as temperature and pressure increase [22A]. From an investigation of thermal bonds between miniaturized electronic devices and their heat sinks, diamond has been found to be highly effective [28A].

Numerical solution methods have already been mentioned in prior paragraphs of this section, and other numerically orientated papers will now be cited. General orthogonal curvilinear coordinate systems have been incorporated into finite element heat-conduction analysis [50A]. As examples of the viability of the finite element method for solving problems of simultaneous heat and mass transfer, results have been obtained for the drying of brick and for moisture transfer through a basement foundation [15A]. Special finite-difference equations have been derived to improve the accuracy of solutions near sharp corners [4A]. The error in a finite difference solution associated with a discontinuous boundary condition is smaller for a nine-point difference approximation than for a five-point approximation [48A]. A highly efficient finite-difference computer program for solving Poisson's equation suppresses all possible operations involving zero and one and uses minimum storage [34A]. An improved Monte Carlo method was proposed in which results are obtained only on the boundaries of standard figures inscribed within a solid; temperatures at interior points of the inscribed figures are then calculated by analytical techniques [69A].

Some attention has been given to other types of solution methodologies. Perturbation methods were shown to be highly effective for steady conduction problems with temperature-dependent thermal conductivity and specific heat [1A]. A hybrid method, involving the use of a digital computer and an RC network, has been proposed for solving transient problems with variable properties [10A]. It has been demonstrated that Gauss' principle of least constraint merits inclusion among the available variational methods for solving linear and nonlinear transient heat-conduction problems [64A]. To achieve a more accurate solution, the standard heat balance integral is supplemented by an additional integral condition derived by multiplying the energy equation by the temperature and then integrating over the solution domain [68A]. To assist in the evaluation of the transient response of a slab with nonuniform initial temperature, several relevant series have been evaluated, and the values are presented graphically [62A].

Certain aspects of particulate and composite materials were investigated. The thermal conductivity of hollow glass microspheres was found to be about one and a half times that of stagnant air. The experiments also showed the microspheres to be an effective opacifier of thermal radiation when added to powder insulations [55A]. The cooling rate of a solid particle with irregularly shaped surfaces is much higher than that of a corresponding particle having the same volume but a smooth surface [56A]. A microcontinuum model of heat conduction in materials with inner structure successfully predicted thermal conductivities for such diverse substances as human blood and aluminium spheres in silicon rubber [47A]. Starting with a variational equation governing the micro-conduction, an equation has been derived for the macro-conduction in composite materials which contain microstructure effects [5A]. By the use of a method developed for studying wave propagation problems, a continuum theory was developed for diffusion-type processes in a laminated composite with periodic microstructure [38A].

Several papers dealt with specific problems of steady and transient heat conduction. The steady conduction of heat as it flows from an infinite medium into a slender highly conducting disk and then into a line sink at the disk center is solved by perturbation analysis [65A]. For a thermally conducting solid containing a crack, the perturbed temperature field in the vicinity of the crack has been determined [2A]. The eigenfunctions corresponding to the zero eigenvalue in a separation of variables solution in rectangular coordinates can be employed to yield a meaningful temperature solution [21A]. The concept of the critical radius of insulation has been generalized to account for simultaneous convection and radiation, with account being taken of the possible variations of the convection coefficient with radius and temperature difference [54A].

A study of transient heat transfer in insulation-coated wires took account of a variety of thermal boundary conditions at the external surface of the insulation [29A]. A solution for the temperature rise produced by a heat-generating layer in contact with a large body was used to study the temperature distribution in thin-film nichrome resistors under transient conditions [19A]. The available analytical solution for the time-varying temperature at the heated bore of a large cylindrical solid has been extended to a larger range of times and generalized via a superposition integral to accommodate prescribed variations in bore heating [16A]. Heat pump applications motivated solutions for transient heat conduction between an array of buried pipes and the earth [45A].

For solids subjected to successive periods of surface heating and cooling with different surface heat-transfer coefficients for the respective parts of the cycle, a proper cycle-average heat-transfer coefficient has been formulated [31A, 32A]. In experiments in which heat was transferred through the interface between two solids that were cyclically brought into contact and separated, it was found that a significant reduction in thermal resistance could be achieved by increasing the impact with which the surfaces made contact [27A]. The thermal analysis of a slab moving from a chamber at one temperature to a second chamber at a different temperature is similar to the Graetz problem for slug flow in a duct [66A]. Automatic welding was modeled as a moving point source of heat, with conduction being the dominant mode of transfer [39A].

Theoretical work has continued on the hyperbolic heat equation and on materials with memory. According to the theory of thermoelasticity, a temperature wave can propagate at a finite wavespeed in a rigid heat conductor [36A]. A finite heat propagation speed induces two stress waves in an elastic medium rather than the single wave predicted for conventional infinite-speed thermal propagation [30A]. The deficiencies of wave solutions of the conventional transient (i.e. parabolic) heat-conduction equation are explored and, by this, the derivation of the hyperbolic heat-conduction equation is motivated [7A, 37A]. Sufficient conditions are given for the hyperbolicity of the equation of linear heat conduction for materials with memory [17A]. The method of energy integrals was used to establish the stability characteristics of temperature fields in heat conductors with memory [44A].

In a highly mathematical treatment, the stability characteristics of the solutions for nonlinear internal heat generation have been investigated [12A]. The conventional heat-conduction laws were deduced by expressing the temperature at a point as a space and time average of temperatures at adjacent points and at previous times [60A].

CHANNEL FLOW

Papers dealing with heat transfer in ducts covered a broad range of topics. Particular attention was given to complex flow passages (encompassing augmentation devices), to solidification of flowing liquids in ducts, to laminar entrance region analyses, and to turbulent analyses involving various turbulence models.

Studies of complex flow passages were motivated by heat exchanger applications. Detailed measurements of the transfer coefficients on the fins of a fin and tube heat exchanger revealed the presence of vortex systems which enhanced the values of the coefficients [36B]. In a corrugated-wall fin and tube heat exchanger, the heat-transfer coefficients on the windward corrugations are appreciably higher than those on the leeward corrugations [16B]. Mass-transfer experiments have demonstrated the presence of secondary-flow vortices in corrugated wall channels [17B]. Heat-transfer coefficients for laminar flow of water and glycol in a tube with twisted-tape inserts exceeded those for an unaugmented tube by as much as a factor of nine [21B]. The use of a helically twisted inner body in an annular turbulent airflow resulted in heat-transfer augmentation whose extent was very sensitive to the pitch of the helix [33B]. A finite element solution for fully developed laminar heat transfer in an internally finned tube revealed that there is an optimum number of fins which maximizes the heat transfer [28B].

The turbulent heat-transfer coefficients in a heated tube downstream of a tee are substantially larger than those in a conventional turbulent pipe flow [45B]. The Nusselt number at the point of reattachment of the separated flow downstream of a partial blockage in a duct is significantly affected by the extent of the blockage [39B]. A study of the turbulent velocity field for longitudinal flow in a rod bundle indicated the presence of secondary flow [5B]. It was demonstrated that the method of asymptotic expansions is applicable to the calculation of flow distributions in rod bundles or in coupled, parallel channels [26B].

A number of papers dealt with the freezing of flowing liquids. Water, Wood's metal, naphthalene, paraffin wax, and olive oil were employed in experiments to determine how far into a cooled tube a liquid could penetrate before freezing and plugging occurred [6B]. A solidification process involving a warm liquid flowing over a cold wall was characterized by a frozen layer thickness which grew at first, but later diminished when the convection from the liquid exceeded the conduction into the wall [11B]. Liquid phase subcooling appears to be unavoidable in internal solidification studies involving filtered tap water and does not appear to be influenced by the presence of additional particulates in the liquid, tube surface roughness, or vibration [31B]. With the assumption that the axial variations in the liquid–solid interface are gradual, the equations for liquid solidification in the combined hydrodynamic and thermal entrance region of a tube reduce to those for single phase flow with a modified pressure gradient [22B]. The blockage due to freezing which occurs as a hot fluid is poured into a cold-walled cavity or mold has been analyzed [27B]. The solidification characteristics of a flowing liquid are an important consideration in the analysis of a hypothetical disruptive accident in the core of a liquid-metal-cooled fast breeder reactor [12B].

The laminar entrance region continues to attract interest. Both the entrance region and the fully developed Nusselt numbers for laminar flow in a semicircular tube are higher than those in a circular tube [20B]. A finite difference solution for laminar flow and heat transfer between concentric spheres indicated the presence of flow separation when the Reynolds number attains a sufficiently large value [2B]. Entrance region and fully developed laminar Nusselt numbers, obtained via the Kantorowich method of variational calculus, are tabulated as a function of cross sectional aspect ratio for rectangular and elliptical ducts [23B]. A finite element method for laminar flow and convective heat-transfer problems was applied to a diverging channel with plane walls [25B]. Linearization of the inertia and convection terms yields satisfactory entrance region results for laminar flow and heat transfer in a porous-walled tube [42B].

The thermal entrance region for combined Couette/Poiseuille flow is another variant of the classical Graetz problem [9B]. The laminar entrance region in a parallel plate channel was re-solved using an integral (Karman-Pohlhausen) method with a higher order polynomial than that used in previous integral analyses [32B]. A study of simultaneously developing laminar velocity and temperature distributions in a tube underscored the importance of radial convection [24B]. The coupled laminar heat and mass transfer in the entrance region of a duct was solved as an eigenvalue problem [29B], as was the laminar mass transfer in the presence of a heterogeneous chemical reaction [3B]. In a study carried out to evaluate concentration and temperature profiles in a tubular flow reactor, it was found that the results were markedly affected by the heat of reaction [15B].

Turbulent flow analyses and experiments have also been reported. The $k-\varepsilon$ turbulence model, when applied to developing flow and heat transfer in tubes and ducts, predicted a minimum in the streamwise variation of the Stanton number [40B]. Solutions for turbulent channel flow based on a modified mixing length model showed many of the same features as the results from the $k-\varepsilon$ model [10B]. Turbulent heat transfer in an annulus with time-varying wall heat flux was solved by superposition; the general solution was applied to the case where the heat flux varies exponentially with time [13B]. Various parameters in a mixing length formulation for heat transfer in rough pipes were deduced by comparison with experiment [19B]. Turbulent heat transfer in a parallel-plate channel was analyzed as an eigenvalue problem (Graetz-type solution) using an algebraic model for the eddy diffusivity [37B].

Results of numerical solutions for turbulent pipe flows near the thermodynamic critical point revealed that the thermal entrance region is longer than that for constant property fluids [38B]. In an experimental study of turbulent heat transfer to supercritical and subcritical CO_2 in a horizontal pipe, the effects of buoyancy caused enhanced heat transfer at the bottom of the pipe and reduced heat transfer at the top [1B]. Entrance region experiments for airflow in a uniformly heated rectangular duct with simultaneously developing velocity and temperature profiles revealed the presence of laminar and transition regions near the duct inlet whose lengths diminished wth increasing Reynolds number [41B].

The Petukhov correlation equation for turbulent pipe-flow Nusselt numbers has been generalized to accommodate low Reynolds numbers, entrance region effects, and property variations [14B]. To obtain an accurate predictive equation for the heating or cooling of superheated steam, a variable-property factor should be appended to the conventional Nusselt–Reynolds–Prandtl correlation (i.e. Dittus–Boelter) [30B].

Non-Newtonian and particle-laden flows have been investigated. Laminar heat-transfer coefficients for Newtonian and viscoelastic liquids flowing in helical coils were found by experiment to be higher than those in straight tubes under comparable flow conditions [34B]. Experimental studies of laminar heat transfer have been performed for several non-linear viscoplastic greases in tubes having several diameters and lengths [8B]. The non-Newtonian behavior of laminar blood flow was modeled by the Casson stress–strain relation in a study of heat transfer in the entrance region of a tube [43B]. Enhanced laminar heat-transfer coefficients in the entrance region of a tube containing a flowing suspension are primarily due to increased tube wall shear rates [44B]. The introduction of a spray of cold liquid droplets into a duct is an effective method for the rapid cooling of a hot gas discharge [18B].

Some theoretical work involved stability and control theory. Linear stability theory, when applied to water flow in a concentric annulus, indicated an earlier onset of instability when the inner cylinder was heated and account is taken of the temperature dependence of the viscosity [7B]. The analysis of thermal instability of a horizontal fluid layer confined between two plates subjected to a vertical magnetic field was extended to the case in which there is a throughflow (i.e. Hartmann flow) [46B]. Optimal control theory was employed to solve the problem of attaining a specified temperature distribution at the exit of a tube for laminar flow conditions [4B].

A partially parabolic flow is one in which influences are transmitted from downstream regions to upstream regions only by way of pressure. A numerical scheme for handling partially parabolic duct flows has been devised by Pratap and Spalding [35B].

BOUNDARY LAYER AND EXTERNAL FLOWS

The reported work in the area of boundary layer and external flows includes laminar and turbulent boundary layers, free jets, impinging jets, and flow over a cylinder.

An experimental study of a turbulent boundary layer with alternating adverse and favorable pressure gradients is reported [52C]. The drag and heat transfer on rough plates have been measured for various Prandtl numbers [16C]. Measurements have been made to determine the local anisotropy in heated and cooled turbulent boundary layers [38C]. A study of spanwise nonuniformity of a nominally two-dimensional turbulent boundary layer is reported [18C]. A high Mach number turbulent boundary layer on the wall of a conical nozzle has been experimentally investigated [4C]. Measurements are made for the free-surface temperature distribution of a falling water film [7C].

Boundary layers on curved surfaces have formed the focus of a number of investigations. A method for calculating curved shear layers has been described [50C]. A study of heat transfer in a laminar wall jet over a curved surface has been reported [46C]. The flow field of a laminar cylindrical wall jet has been studied [45C]. An analysis is presented of the second-order effects associated with curvature and other factors in self-similar laminar boundary layers [1C]. The steady laminar flow through circular pipes having varying curvature has been analyzed [39C]. Measurements are reported for the growth of a turbulent boundary layer in a bend; the behaviour on the convex side is found to be quite different from that on the concave side [37C].

Numerous papers are aimed at predicting the details of laminar and turbulent boundary layers. A comprehensive correlation has been presented for forced convection on flat plates [13C]. An expression is developed for the mean temperature profile in the near-wall region of a turbulent boundary layer for various Prandtl numbers [28C]. Skin-friction coefficients for turbulent boundary layers at low Reynolds numbers are predicted by using a form of the mixing-length hypothesis [43C]. An integral method has been used to calculate turbulent boundary-layer development for certain external-velocity distributions; it is found that different values of the initial momentum thickness produce a range of equilibrium boundary layers [21C]. The effect of variable physical properties on drag and heat transfer on a flat plate has been studied through numerical solutions [53C]. An approximate method has been described for the solution of non-similar laminar boundary layers [41C]. The two-dimensional laminar boundary layer has been calculated by a least-squares finite-element method [35C]. An inverse method (i.e. prescribed wall shear stress rather than the external velocity) is presented for compressible laminar and turbulent boundary layers [9C]. Calculations for heat transfer through a turbulent boundary layer with an unheated starting length are performed on the basis of the surface renewal model [51C]. A two-equation turbulence model is used to predict the velocity field of two-dimensional turbulent boundary layers; situations with a variety of pressure gradients, namely those featured in the 1968 Stanford Conference, have been predicted with good agreement with experimental data [42C]. Semi-similar solutions have been reported for three-dimensional laminar boundary layer [56C]. A solution procedure for three-dimensional boundary layers is described; it uses orthogonal curvilinear coordinates [10C]. Solutions for *unsteady* boundary layers have been obtained [6C, 12C, 55C]. The compressible laminar boundary layer on a yawed cone is solved by a finite-difference method [47C]. A two-equation turbulence model is used to predict the development of a compressible turbulent boundary layer [36C]. The interaction of a shock wave with a boundary layer is analyzed [24C, 49C]. Numerical solutions are presented for the flat-plate boundary layer of a micropolar fluid [20C]. Heat transfer across turbulent liquid films is predicted by combining the standard heat-transfer concepts with the results of film hydrodynamics [8C]. An analysis is made for two parallel adjacent streams with interfacial mass transfer [34C].

Among the free jet investigations, an experimental study reports the velocity and concentration profiles for a carbon dioxide jet injected into air [11C]. Experimental data are presented for the velocity and temperature profiles resulting from rectangular jets of different aspect ratios; the jets are found to behave initially like two-dimensional jets, but become similar to axisymmetric jets in the far downstream region [48C]. Studies of the mean and conditional temperature and velocity profiles are reported for a hot turbulent jet [26C, 27C]. A turbulence model has been applied to horizontal free-shear flows under the influence of buoyancy [19C]. Heat transfer to laminar falling liquid jets has been analyzed by an integral method [40C].

The impinging jets have been studied experimentally and analytically. Impinging jet experiments involving air and carbon dioxide have been reported [17C]. The shear stress distribution resulting from an impinging jet is measured; the results are related to the heat transfer on the impingement surface [5C]. Local mass-transfer coefficients resulting from the impingement of a row of circular jets are measured by means of the naphthalene sublimation technique [32C]. An impinging laminar jet with suction at the impingement surface is analyzed by a finite-difference method [54C]. A correlation has been developed for the stagnation region heat transfer in particle laden hypersonic flows [22C].

The flow over a circular cylinder is the subject of several investigations. Measurements are reported for the mean velocity and turbulence quantities in an axisymmetric turbulent boundary layer along a circular cylinder [3C]. A study has been presented for the heat transfer from a cylinder in crossflow [23C]. The local heat transfer from a circular cylinder is experimentally investigated for Reynolds numbers around the critical value [57C]. The effect of free-stream turbulence on the heat transfer from a circular cylinder has been studied [31C, 30C]. The axisymmetric turbulent boundary layer along a circular cylinder is described by the method of matched asymptotic expansions; the existence of a log-law region and a defect-law region is shown [2C]. An analysis is made of the heat transfer from an isothermal hot wire in a low Reynolds number flow having a small sinusoidally fluctuating velocity superimposed on the mean velocity [15C]. Unsteady laminar boundary layer on an impulsively started circular cylinder has been investigated [25C, 29C]. Heat-transfer coefficients from spheres were measured in the naturally turbulent outdoor environment; the value of the Nusselt number obtained outdoors was up to 2.2 times the value found in low turbulence wind tunnels [33C].

Among diffusion-related studies, the diffusion from a line source in a turbulent boundary layer has been experimentally investigated [14C]. A linear stability criterion is developed for the case of a nonlinear concentration-dependent diffusion process [44C].

FLOW WITH SEPARATED REGIONS

Single bodies

A direct method of calculating through regions of separated flow is given [32D]. This problem is complicated by the existence of a separation point singularity which occurs whenever the pressure gradient is prescribed in the neighbourhood of separation. When a circular cylinder, distorted into a wavy form, moves transversely in a fluid at low Reynolds number, the wake of the cylinder is remarkably different [16D] from a straight one, but the periodic character of wake shedding seems to remain unchanged. An analysis is given [21D] for the velocities and temperatures in the turbulent wake of a heated cylinder with intermittency taken into account. Numerical solutions of the Navier–Stokes equations were obtained [22D] for separated flows around a circular cylinder at $Re = 40, 80$ and 200 using three finite different techniques. In [37D] the behaviour of the heat flux rate in the separation region near a double step at the entrance to an enlarged flat duct is correlated with measurements of heat transported by turbulence $\overline{v'T'}$. Both experimental and numerical results on laminar boundary layers on a sphere show that increasing the sphere temperature above that of the surrounding water shifts the laminar separation point slightly to the rear [40D].

Amr and Kassoy [1D] analyze reattachment of a blownoff supersonic boundary layer subsequent to injection cutoff. Fluid injection through a cavity has significant effects on the flow pattern and laminate heat-transfer rates. The greatest reduction in heat transfer is evidenced at the reattachment point on the downstream cavity wall [18D]. An experimental investigation of the turbulent near-wake regions of several two-dimensional and axially-symmetric bluff bodies helps explain the similarity and the mechanisms of formation of vortices [41D]. Reference [27D] describes rear stagnation point location in the subsonic near wake.

Packed and fluidized beds

Transport phenomena in non-homogeneous porous media are described [29D]. Recent research in the field of capillary-porous material transport processes at the Institute of Heat and Mass Transfer of the BSSR Academy of Sciences is summarized [23D]. Accurate bounds for the effective diffusion constant and for Darcy's constant in porous media are obtained by a new variational formula [10D]. A theoretical analysis of an internally-energized, porous reactor is presented [28D] for both constant and temperature-dependent rate of generation. The concept of generating temperature dependent rate of heating within a prous element is aimed at gaining stability in operation and protecting the solid from burnout. A boundary-layer integral balance method is applied to determine the transfer potentials of heat and mass in porous bodies of cylindrical geometry [34D]. Pismen [31D] studies convective currents induced by chemical reactions in partially-filled porous media. Reference [39D] concludes that for up to 48% solid phase volume fraction, it is impossible, from a heat transfer point of view, to construct a thermal conductivity model that accurately represents heterogeneous porous materials.

Reference [6D] investigates the transient temperature distribution within packed beds after being subjected to single blow heating. The boundary conditions do not require that fluid or solid temperatures be specified at the initial and final bounding surfaces. The Knudsen equation for flow through circular pores may be used for most porous materials without fear that a noncircular pore cross section will alter the conclusions significantly [11D]. The evaporative heat-transfer process in porous media is not clearly understood. Using a flow visualization rig, [9D] shows that both vapor and liquid regions coexist at the heating surface over a wide range of heat fluxes. General solutions for small Peclet number heat or mass transfer in concentrated two-phase particulate systems submerged in arbitrary Stokesian flows with arbitrary temperature or concentration boundary conditions are given [45D] that were obtained using regular perturbation expansions of the dependent variables in powers of the Peclet number. The use of a contact resistance as a technique to match predictions with practical results is very common in granular media heat transfer. In [5D] the use of contact resistance is shown to be a source of error due to wide variability with geometry.

Methods for determination of heat and mass transfer in packed beds are surveyed and compared [14D]. The influence of thermal conductivity in the reactor wall on total axial conductivity and the reduction in overall heat transfer due to axial heat conductivity is correlated [13D] in the form of an effectiveness factor. Reference [3D] describes the effective radial thermal conductivity of various forms of particulate feeds through which gas is flowing. Lou and Wang [24D] give temperature distributions in cylindrical packed beds. The agreement of heat- and mass-transfer data in packed beds confirms that particle-to-particle transfer is negligible in the turbulent region [17D]. A model to simulate heat transfer accompanying melting in a layer of granular particles is proposed [30D]. Reference [2D] describes application of the limiting current method to mass transfer in packed beds at very low Reynolds numbers ($Re \ll 1$).

A generalized analysis to describe the overall process of gas-particle heat transfer in shallow fluidized-bed heat exchangers is developed [25D] and a laboratory scale cross-flow fluidized bed heat exchanger was built and operated to investigate new heat-transfer correlations [26D]. Saxena and Vogel [36D] describe the properties of a dolomite fluidized bed reactor normally used as a combustor for a range of particle sizes and shapes at minimum fluidization. General theories on fluidized bed heat transfer appear in [46D] and [42D]. Heat transfer in the thermal stabilization zone of a liquid-fluidized bed involves the distance from the grating to the point where the heat-transfer coefficient is constant [19D].

Pulsation of fluidizing air leads to an 80% increase in the heat transfer over normal fluidization for large particles at air flow rates a little above incipient fluidization [4D]. The enhanced heat transfer for a vertical heater plate immersed in a vibrated powder bed is attributed [15D] to the scouring of the gas sublayer on the surface of the heater by the particles. Other studies of heat transfer from immersed surfaces in liquid fluidized beds are presented [35D]. Entrainment of solid particles by gas jets discharged downward through slotted nozzles into bubble-free beds is considered [8D]. The electrical resistance of fluidized beds is determined [43D] along with the electrode-temperature in a unit with cylindrical electrode geometry.

Time-averaged temperature profiles are measured downstream in liquid-fluidized beds by injecting hot water. Eddy thermal diffusivities are computed using Taylor's theory of eddy diffusion [33D]. Siegel discusses the effect of distributor plate-to-bed resistance ratio on the onset of fluidized bed channeling [38D]. A model of bubbles rising in an unbounded fluidized bed is presented [7D]. The influences of bubble-induced heat transfer in gas fluidized beds is given in [20D]. For gas fluidized beds of small particles operating below the radiative temperature level, transient conduction into the emulsion phase is responsible for at least 90% of the heat transfer and the remainder is contributed by the superimposed gas convection. The first statistically significant measurements of propagation properties of voidage waves in fluidized beds [12D] have shown that the breakup of these waves is followed by a mode of motion suggestive of bubble formation. Finally, Werther [44D] explains the significance of bubble coalescence for the design of gas/solids fluidized beds.

TRANSFER MECHANISMS

The transfer mechanisms in turbulent flows form the focus of most of the work in this category.

Detailed measurements of the fluctuating velocity and temperature fields have been reported in a variety of situations. A trace particle method for describing three-dimensional turbulent velocity field has been presented [11E]. Bursts in a turbulent boundary layer in zero pressure gradient and in an axisymmetric jet have been experimentally studied [2E]. Measurements have been reported for a turbulent boundary layer subjected to random fluctuations in the external stream [5E]. A study has been made of high-frequency wall-pressure fluctuations in turbulent boundary layers [4E]. A mixing layer with unequal free-stream turbulence levels in the two streams has been investigated [16E]. Turbulent shear stresses in hypersonic boundary layers have been measured [12E]. A study is presented of the decay of turbulence in a closed vessel [25E]. An experimental investigation of special turbulent flows is reported; these are turbulent shear flows with quadratic mean-velocity profiles generated by using a honeycomb and parallel-rod grids [20E]. Turbulent Prandtl numbers have been measured in the near-wall region in small tubes [14E]. An examination of the wall structure of the turbulent boundary layer has been made by the use of hot-wire rakes and conditional sampling techniques [3E]. Studies of dispersion from a heated wire in a turbulent boundary layer [21E] and from a line source in grid turbulence [22E] have been reported.

Some work has been published on the phenomenological models of turbulence. A modified law of the wake for turbulent shear flows is presented [9E]. The surface renewal model of turbulence is discussed by reference to interfacial conditions [23E]. An algebraic stress model has been proposed for stratified turbulent shear flows [15E]. A Reynolds stress model for turbulent corner flows has been presented [7E], and its results have been compared with experimental data [8E]. Buleev's model for turbulence has been examined; the model has been found to be successful in only simple configurations [18E]. A turbulence model involving differential equations for the Reynolds stresses is developed for low-Reynolds-number turbulence [10E]. A second-order closure for turbulence is used to compute variable-density flows [13E]. The variation of experimentally determined turbulent Prandtl and Schmidt numbers is examined for free turbulent flows; for jets and wakes, these numbers are found to vary by a factor of about 2 across the layer [19E].

A method is presented for calculating the temperature profile in a turbulent flow from the amplitude distribution of measured temperature fluctuations at a fixed position in the flow [17E]. A theory of turbulence decay for an axisymmetric turbulence temperature wake is described [6E]. A kinetic theory of turbulence correlations has been developed for turbulent compressible flows [26E]. The temperature fluctuations in a turbulent shear flow are modeled by a ramp-like signal with superimposed Gaussian fluctuations (1E). Burger's model of turbulence is used to calculate the energy decay with various initial energy spectrums [27E]. A statistical theory of one-dimensional turbulence in a compressible flow has been presented [24E]. A statistical formulation of unsteady homogeneous turbulence has been described [28E].

NATURAL CONVECTION

The outpouring of papers on various aspects of natural convection continues unabated. As usual, there is considerable interest in flows within enclosures, in boundary-layer flows, in thermal plumes, and in aspects of combined convection wherein buoyancy effects are superimposed on a flow field producing alterations in the velocity distribution and in the heat transfer. Other studies consider flows in porous media, including energy recovery from geothermal reservoirs, flows in which the forces inducing the flow result not only from buoyancy effects due to temperature but also from buoyancy effects due to concentration difference, and surface tension induced flows as well. Thermal diffusion effects and flow of non-Newtonian and micropolar fluids are also examined.

For the case of a horizontal layer heated from below in what is called Bénard convection or Rayleigh–Bénard convection, studies covering stability, laminar flow and turbulent flow have been reported. The critical Rayleigh number is obtained from consideration of the dissipative process in a fluid [83F]. The prediction of the critical Rayleigh number for the non-linear density distribution obtained in a horizontal layer of water cooled from below to the maximum density point agrees well with experimental measurement [59F]. A numerical simulation [54F] finds three-dimensional (twice periodic) disturbances starting at a Rayleigh number of about 5600; the predicted Nusselt numbers in this study agree well experiments up to a Rayleigh number of 25 000. Another three-dimensional numerical analysis of laminar natural convection considers heating from below in fluids in different shaped enclosures [66F]. Temperature oscillations were measured in a mercury bath heated from below [67F].

The range of validity of the Boussinesq approximation has been examined as applied specifically to natural convection in air and water [34F]. An analysis of the heat transfer at high Rayleigh number fits earlier experimental data very well [55F]. Measurements of the heat flux and velocity and temperature fluctuations have been carried out in a layer of air up to a Rayleigh number of about 7×10^9 [30F].

Linear stability theory is used [88F] to obtain the onset of flow in a melting layer heated from below in which the fluid's density decreases with temperature. Linear stability criteria are also applied to predict the onset of convection in a porous medium with internal heat generation [32F] and with a periodic temperature variation on the lower boundary of the porous surface [17F]. A temperature dependent viscosity can significantly affect the critical Rayleigh number for the onset of convection in a porous medium [46F].

Measurements of the heat transfer in a porous layer slightly above the critical Rayleigh number agree with earlier estimates of the upper bounds for the heat transfer [14F]. A computer simulation of the natural convection in a porous medium as might apply in geothermal energy recovery includes effects of confinement, variable permeability, and thermal boundary conditions [73F].

Thermal diffusion in a binary gas mixture in a porous medium results in a critical Rayleigh number at the onset of flow, which can be either greater than or less than that for the case of a pure fluid [52F]. The influence of the Soret effect on the thermal instability of a two component fluid layer has been analyzed [90F]. A non-linear analysis for the case of a positive Soret coefficient gives the relationship of the Nusselt number to the Rayleigh number [68F]. The influence of a negative Soret coefficient on stability of the flow of a real salt solution has been examined [15F].

The measured critical Rayleigh number for the onset of thermohaline convection compares favorably to predictions by both linear and energy methods [94F]. Molecular diffusion is the dominating transport process in the thermohaline region between two convecting horizontal layers at different concentrations [56F].

Instability induced by combined buoyancy and surface tension has been studied in a region where the fluid has a maximum density as a function of temperature [96F]. A micropolar fluid is one in which the length of the molecules is not negligible compared to the characteristic geometric length of the flow. The stability of such fluids in a horizontal layer when heated from below has been examined in two studies [2F, 28F].

The heat transfer from a single heated horizontal surface facing upwards is often comparable to the heat transfer across horizontal fluid layers. The convection from horizontal plates of different shapes has been measured in both the laminar and turbulent regimes [5F]. Laminar flow analysis of the mass-transfer convection equivalent to a heated plate facing either upward or downard has been described [8F]. The instability following transient heating of a plate facing upwards has been obtained [74F]. The importance of free convection phenomena in controlling the burning from a horizontal fuel surface has been alanyzed [24F]. A numerical study of buoyancy driven flows as would occur in the atmosphere has been reported [97F].

Studies on heat transfer to enclosures include a number of different geometries. The turbulent natural convection of liquified gases has been studied in containers of different shapes with a resulting simple correlation of Nusselt number as a function of Rayleigh number [26F]. Numerical predictions and experimental measurements were carried out for natural convection of a heat generating fluid within different enclosures [47F]. Correlations for the heat transfer to fluids in horizontal cylinders were obtained using simple parameters [36F].

An experimental and numerical study of natural convection in the annulus between horizontal concentric cylinders gives excellent agreement of measurement and analysis [50F]. Correlating equations have been obtained over a range of conditions for natural convection heat transfer between concentric horizontal cylinders [51F]. An analysis of free convective heat transfer between two horizontal concentric cylinders shows the effect of a density inversion [79F]. Three-dimensional cellular convection in a cylinder with a free boundary has been analyzed [43F]. The streamlines in the transient cooling of a horizontal cylinder of water through the maximum density point have been determined [20F].

A study of the influence of natural convection in flat plate solar collectors shows the importance of spacing between the collector's surface and the glass cover [13F]. Heat-transfer across inclined fluid layers has been experimentally investigated over a range of Rayleigh numbers and angles of inclination [6F, 38F]. Laminar natural convection resulting from localized heating on the wall of a rectangular enclosure has been analyzed [23F].

A model has been analyzed to indicate the flow instabilities in a vertical layer of fluid enclosed by two plates at different temperatures [61F]. Wave-like temperature variations were found above a critical Rayleigh number for fluids enclosed between two vertical plates [91F]. The flow in an open vertical cylinder whose surface is at a temperature different from that of the surrounding fluid has been calculated including thermal entrance effects [37F]. The effect of a magnetic field on the convection of a ferromagnetic fluid in a vertical layer has been examined [10F]. Combined radiation-convection heat transfer in an electrically conducting fluid in a vertical layer under the presence of a transverse magnetic field has been described [27F].

A number of studies have considered aspects of the natural convection boundary layer along a vertical plate. A simple correlation for the effect of Prandtl number on Nusselt number has been obtained from earlier theoretical analyses [31F]. Local non-similar solutions have been obtained for the laminar flow adjacent to such a surface [45F]. The effect of discontinuities in surface conditions on the heat transfer from a vertical plate has been reported [58F]. Universal velocity profiles have been used in an integral analysis to predict the turbulent flow heat transfer from such a surface [53S]. A local non-similarity analysis has been applied to convection when a vertical surface is placed in a stratified fluid [18F]. The relationship between artificially induced and naturally occurring transition of a natural convection boundary layer has been described [42F].

Numerical calculations of the growth and non-linear interaction of secondary motions superimposed on the boundary layer on a vertical plate have been made [7F]. Combined heat and mass transfer produce buoyancy forces which affect flow transitions when the Lewis number is not unity [12F]. Numerical integration of the flow equations for an electrically conducting fluid adjacent to a hot vertical plate in a strong magnetic field has been reported [92F].

An analysis of the convection about a thin vertical cylinder immersed in a fluid of low Prandtl number delineates the flow in the outer and inner regions around the cylinder [25F]. Experimental results for the natural convection heat transfer from a horizontal tube to a fluid near the critical point can be correlated using standard dimensionless heat-transfer parameters; such measurements were performed using a number of different fluids [11F, 84F].

Experimental measurements of the heat transfer from a melting ice layer to surrounding water indicate a minimum rate of heat transfer occurs not when the surrounding water is at the lowest temperature studied, but when it is approximately 5.6°C [9F]. Transient natural convection mass transfer from a plate yields an overshoot with a step change in boundary conditions as had been observed earlier [16F]. Both steady-state and non-steady-state natural convection heat transfer to a power law fluid at high Prandtl number have been considered [82F]. Non-linear analysis of flow in a porous medium adjacent to a horizontal surface has application to heat transfer in geothermal reservoirs [19F].

Experiments and an approximate analysis for heat transfer from prolate and oblate spheroids agree well with each other [71F]. Extensions of that study in which the prolate spheroid is taken to the limit of a vertical needle have been presented [70F]. A prediction of laminar and turbulent free convection from elliptic cylinders agrees well with other investigators' results at the extremes of eccentricity, i.e. from vertical plates and horizontal cylinders [69F]. Laminar natural convection from downward-facing heated blunt bodies to liquid metals has been analyzed for application to a core catcher in a fast nuclear reactor [35F].

Convection in some three-dimensional flows including that about inclined plates and circular cylinders has been examined numerically [64F] and in the case of inclined cylinders experimentally [63F]. Local similarity and non-similarity methods are used to determine the convection about a vertical cylinder embedded in a porous medium [60F]. Temperature and velocity profiles in polymer solutions around heated spheres have been obtained [4F]. Experiments and an integral analysis yield the heat transfer by convection to non-Newtonian dilatant fluids surrounding a horizontal cylinder with different boundary conditions [48F].

Several authors consider buoyancy-induced convection in rotating systems. Small disturbance theory is used to predict the stability of convection in a narrow rotating annulus with a heated inner wall [49F]. The effect of rotation on a fluid layer heated from below has been analyzed [41F]. Experiments on the natural convection in a rotating differentially heated cylindrical annulus have been conducted with fluids of different Prandtl number [29F].

The rise of a buoyant laminar plume emanating from a discrete heated source has been studied using a shadowgraph system [81F]. An approximate solution has been obtained in closed form for the laminar-convection velocity and density fields due to a buoyant source [89F]. The interaction of two laminar plumes originating from line sources of unequal strength are observed using an interferometer [33F]. The swaying motion of a plume above a horizontal heated plate has been postulated to be self-excited [3F].

Experiments on turbulent flow in buoyant jets agree with predictions from an integral analysis using an entrainment coefficient approximated from isothermal jet studies [78F]. A model for the flow of a heated liquid plume including surface effects is compared to earlier models and experiments [80F].

Studies of combined convection in which the flow field is the result of both forced flow and buoyancy effects have been conducted in a number of different situations. These include boundary-layer flows, duct flows, and flows within porous media. The effect of starting length on non-similar solutions for mixed convection on a vertical plate has been calculated [1F]. The use of asymptotic results at large Prandtl number are found to apply even at Prandtl number of one for heat transfer by mixed convection about a semi-infinite isothermal plate [93F]. Aiding flow of a Bingham plastic on a vertical flat plate has been analyzed [57F]. The effect of freestream oscillations adjacent to a vertical porous plate with suction has been analyzed with the plate either cooled or heated [86F].

A power series solution yields the velocity and temperature distributions for combined convection in a laminar wall jet along a vertical plate [72F]. Increased heat transfer is found for combined convection in aiding flow along a vertical cylinder with uniform heat flux [62F]. Boundary-layer analysis has been applied to aiding flow about a horizontal cylinder [87F].

Combined convection in water near its maximum of density flowing over a horizontal heated plate has been studied to determine the critical Rayleigh number [21F]. Longitudinal vortices above a critical Rayleigh number are found with a Blasius flow over a heated horizontal plate [95F].

The flow of air in a horizontal channel is found to be more sensitive to heating from below in the thermal entrance region than in the fully developed region [44F]. Another study of stability in the entrance region for horizontal flow in a channel includes the effect of axial heat conduction [22F]. With combined convection in a horizontal tube, the variation of temperature with viscosity can give a significant increase in the rate of heat transfer [40F]. A numerical analysis gives the heat flow for combined laminar convection in inclined rectangular channels [65F]. Experiments on combined convection in inclined circular tubes agree with predictions at low Rayleigh numbers and low Reynolds numbers [75F]. Heat-transfer experiments have been performed on water flowing in horizontal and inclined tubes at supercritical pressure conditions [85F].

A study of combined forced and natural convection in wet geothermal formations includes the effect of water reinjected into the reservoir [77F]. The stability of throughflow in a porous media when heated from below has been determined [39F]. Combined convection in a vertical annulus containing a micro-polar fluid has been described [76F].

CONVECTION FROM ROTATING SURFACES

The distributions of the velocity and temperature, or Reynolds stresses, and of heat flux and temperature fluctuations were determined [4G] in turbulent incompressible flow through a tube rotating around its axis. An analysis [7G] was performed to obtain friction factors and heat-transfer coefficients on a rotating circular cylinder.

The recirculating, swirling, turbulent flow was predicted [2G] in the cavity between a rotating disc and a stationary shrouded disk. Good agreement with experimental results was obtained for laminar flows; a two-equation turbulence model was used for turbulent flow. Local measurements of the temperature field and of heat transfer for the same type of enclosure with coolant throughflow entering through the rotating shaft and leaving through an annular space at the rim of the rotating disk were reported [8G]. A computer analysis [1G] determined the velocity and temperature field and local Nusselt numbers in an enclosure of the same type with turbulent throughflow.

Heat transfer through a laminar compressible boundary layer on a sphere rotating in a quiescent fluid was analyzed [3G]. An asymptotic solution was obtained [6G] describing heat transfer for closed streamline flow past small rotating particles at large Peclet numbers and small Reynolds numbers. Flow and heat transfer were calculated in a hydromagnetic Ekman layer on a rotating porous plate [5G] under the influence of a transverse magnetic field.

COMBINED HEAT AND MASS TRANSFER

Interest in combined heat and mass transfer centers on applications of mass addition, either local or distributed over a surface, to protect a surface from a hot mainstream. A number of experimental and analytical studies have been reported in this area.

A review of two-dimensional film cooling using slots shows the ranges of validity of previously reported correlating equations for the local film cooling effectiveness [12H]. An examination of the relative sizes of the thermal and velocity boundary layers in two-dimensional film cooling is useful in predicting the effectiveness [11H]. A recent study confirms previous findings that, over a moderate range, an adverse pressure gradient has little influence on two-dimensional film cooling [7H]. The effects of multiple rows of staggered film cooling jets were predicted from the results of a single row of staggered holes using the principle of superposition [13H]. In this study, the lateral average effectiveness was determined. A finite difference procedure [2H] predicts film cooling performance from a single row of inclined jets with laminar flow. The details of the flow field in the vicinity of a jet entering a turbulent boundary layer was measured to enhance the understanding of film cooling performance close to an injection hole [1H]. Photos of helium-filled soap bubbles put in with the secondary jets showed the trajectory of the injected fluid in three-dimensional film cooling. From these streak lines, qualitative estimates of the effects of changes in the hole spacing and inclination were made [4H].

Film cooling applications include high speed flows where compressible aerodynamic effects can be quite important. The effects of the slot height and lip thickness on two-dimensional film cooling in a Mach 6 airstream were measured [8H]. A recent analysis shows that the angle of injection into a hypersonic laminar boundary layer significantly influences the heat transfer [9H].

The flow following uniformly-distributed injection through a surface with the injected fluid having a velocity component parallel to the mainstream has been examined [3H]. An integral solution to the laminar boundary-layer equations with transpiring flow gives simple, yet apparently reliable, predictions of the wall heat flux [17H].

The effect of blowing on heat transfer to a turbine blade has been approximated [14H]. Optimization of the film coolant flow in a gas turbine cascade has been studied including the effects on pressure loss and flow separation [10H].

A model has been established for the flow and heat transfer in a multi-component boundary layer to include the influence of multi-component diffusion [6H]. Another study [15H] shows the effects of thermodynamic coupling on flow in a compressible multi-component laminar boundary layer.

The combined effect of heat and mass transfer from a freely falling drop has been studied [16H]. The transport of heat and salt in a layer across which temperature and concentration gradients have been established has been studied including the influence of turbulence produced by vertically oscillating grids [5H].

CHANGE OF PHASE

Boiling

Studies of evaporation in vertical grooves and capillary tubes [39J] support the hypothesis that fluid flow in and to an evaporating menescus results from a curvature gradient. A theoretical model to determine the required superheat for stable boiling from a cavity has been developed [47J] considering the liquid penetration, the effects of transient heat flux, and the inertial and viscous effects of liquid moving inside the cavity. The initial-to-final vapor density ratio, when significantly greater than unity, strongly influences vapor bubble growth rates in the inertial and the inertial-heat-transfer regimes [51J]. A heat-transfer controlled bubble model has yielded three semi-empirical correlations to predict bubble growth rate, maximum bubble diameter, and maximum bubble growth time for subcooled nucleate flow boiling of water up to 17.7 MN/m^2 [54J]. The problem of bubble growth in the presence of a magnetic field is examined [28J] in the heat-transfer region. The work reveals the existence of a new nondimensional number which physically represents the ratio of pondermotive forces over pressure forces. Heat transfer in nucleate boiling is reduced in the presence of magnetic fields—substantially more for potassium than for mercury. A microlayer mechanism supported by extensive experimental evidence is used to explain the high heat fluxes observed during nucleate boiling [32J]. The data in [23J] comprise a comprehensive set of measurements which substantiates a model for predicting boiling heat flux incorporating microlayer evaporation, natural convection, and nucleate boiling mechanisms.

The hydrodynamic stability approach is used to explain the effect of electrostatic fields on the maximum heat flux [4J]. Heat-transfer crisis in annuli is studied [35J] in which the rate of heat transfer varies longitudinally either sinusoidally or decreases exponentially. Rao and Andrews [40J] describe the effect of heater diameter on the critical heat flux from horizontal cylinders in pool boiling. A large inlet break loss-of-coolant accident in a pressurized-water reactor would cause the flow through the core to reverse within milliseconds. Reference [48J] gives an analysis of critical heat flux with flow reversal transients. Canon and Park [7J] develop a stability criterion for transition boiling and demonstrate that, when it is satisfied for boiling equipment, then stable boiling can be obtained over the entire transition region. The dynamics of the transition region are studied [38J] for flow boiling using an apparatus that includes a feedback control system that permits operation at any point on the boiling curve. Impaction of volatile liquid droplets onto a hot liquid surface is studied [57J]. The transplosion phenomenon (inverse Leidenfrost phenomenon) is examined experimentally for a molten copper–water system [63J].

A three-dimensional variational approach to stability of the vapor film during film boiling from horizontal cylinders leads to results [5J] which agree with data. Marschall analyzes binary, laminar film boiling [31J]. Basu [2J] also deals with film boiling of organic binaries on a horizontal wire at atmospheric pressure. Experiments of film boiling of carbon dioxide generate curves of heat-transfer coefficient vs pressure that take on minimum values at the triple and critical points [21J]. Localized contact between liquid and heating surface was found to exist during stable film boiling that resulted in surface scaling [15J].

A new empirical correlation equation is developed [16J] which permits one to predict the performance of a cylindrical heater in the presence of cross flow and boiling, provided only that its performance in the absence of crossflow (pool boiling) is known. Burnout is investigated with flow of a steam–water mixture in a round tube [26J]. The effects of certain organic additives on boiling are discussed [11J]. Noncircular duct hot patch data, extensively referred to in the literature, have been found to be in error. When these data are corrected and compared with predictions of hot patch dryout using the most recent form of the

Tong F factor [30J], unintelligible results are obtained. In many heat exchangers operating at supercritical pressures, heat transfer in turbulent pipe flow occurs with very large temperature gradients such that the flow core temperature is much below critical and a process known as "pseudo-boiling" occurs [24J].

Condensation

Wilson has shown [61J] that, within the framework of thin film approximations, the solution of unsteady and three dimensional condensation problems can be reduced to the solution of a system of ordinary differential equations, thereby adding to the class of problems that can be solved in closed form. Reference [10J] extends the pioneering work of Sparrow and Gregg on the phenomena of condensation on a rotating disk to include constant axial suction at the permeable condensing surface. Sage and Estrin [43J] apply the analytical methods for treating multi-component systems to film condensation of a condensable component from its mixture with two noncondensables. Epstein and Cho [14J] analyze laminar film condensation on a vertical melting surface—obtaining an integral solution of the boundary-layer equations for one and two component systems. Laminar film condensation equations with combined body force and forced convection of a binary vapor over a flat plate are solved by finite difference and two integral methods [27J]. Generally speaking, the whole region of condensation may be analyzed with good accuracy by approximate integral techniques.

The synthesis of single-droplet constriction resistance solutions with the known droplet distribution leads to a simple correlation for the effect of the condenser material thermal properties on the dropwise condensation heat-transfer coefficient [17J]. In a companion paper [18J], the magnitude of the surface thermal conductivity effect on dropwise condensation heat transfer is determined experimentally. An expression is suggested [56J] for the total condensation length in pipes if the heat-transfer coefficients over a short tube segment is known. The theoretical dependance of heat-transfer coefficients on maximum drop size is incorporated into a new condensation theory giving the dependence of sweeping frequency and heat-transfer coefficient on distance along the condensing surface [41J]. The stability of drops as a function of their size and the slope of the surface upon which they reside has shown that when the angle of inclination of the surface to the horizontal is $\theta = \arctan \pi$, the drops are least stable [1J]. At present there is no commercially acceptable dropwise condensing surface although the motivation for producing such a surface is significant. There is general agreement that dropwise condensation is a heterogeneous process. Reference [12J] demonstrates the direct effect of nucleation site dimensions on dropwise condensation heat-transfer rate. Several attempts have been made to use surface tension forces to reduce the thickness of the condensate films on vertical surfaces and, thereby, reduce the heat-transfer rate. Reference [8J] studies condensation on static and rotating pinned tubes since the addition of pins produces only a small area increase.

Reference [13J] gives a two-dimensional analysis of the effect of precursory cooling on conduction controlled rewetting of a vertical surface. Precursory cooling refers to the cooling caused by the droplet–vapor mixture in the region ahead of a wet front in surface rewetting. Experiments are summarized [42J] that investigate transient radial heat transport effects created by oscillatory turbulent subcooled flow in uniformly heated tubes. Shock [46J] analyzes evaporation of binary mixtures in upward annular flow. Entrance effects increase heat transfer by 20% in a vertical tube with vaporization of water [50J]. A simple procedure is given [59J] to obtain heat-transfer coefficients in the interline region (junction of vapor, absorbed evaporating thin film, and adsorbed non-evaporating wetting thin film). In [19J] the transport reaction mechanism of mist formation in a convective field is discussed on the basis of a "critical supersaturation model". Analyses are performed for mist formation conditions, mist region, and vaporization rate, and are verified using a naphthalene sublimation rate. Kosky [25J] studied the flow of a steam–air mixture containing a fraction (0.5–20 wt %) of mist being swept across a roughened, heated tube.

Two-phase flow

It is often necessary to use simplified (one-dimensional) forms of the conservation equations for many multiphase, multi-component flows. In [62J] the effects of radial distributions of velocities, enthalpies, and void fractions are explained. In [52J] the theoretical study of time varying, two-phase-flow problems in several space dimensions introduced such a complex set of non-linear partial differential equations that numerical solution procedures using high speed computers are required. The ability of one-dimensional balances to predict two-phase pressure drop across abrupt area changes in oscillatory flow has been examined [60J]. New experiments data on the onset of so-called "density wave oscillations" and their frequence are available [44J]. Significant time lag between the system pressure drop and the inlet flow was observed during the unstable operation.

In comparing a theoretical laminar analysis of a horizontal condenser–evaporator tube with data, a 50% discrepancy is reduced to about 15% when the effects of ripples are taken into account [33J]. The flow pattern in a horizontal agitated thin-film evaporator are studied [58J]. Mogro [34J] studies the separation of gas-vapor mixtures by condensation in a vertical tube at Reynolds numbers as high as 450 000. Condensation heat transfer of steam on multiple free falling water jets enveloped by air streams are investigated experimentally [3J]. An integral method is used [49J] to obtain a closed-form expression for the hydrodynamic entrance length for falling liquid films emerging from a flat slit and flowing in laminar flow along an inclined flat plate. Liquid spindle oil falling films are much more laminar-like than turbulent for Reynolds numbers below 6000 [53J].

Reference [20J] predicts the interfacial drag and the height of the wall layer in annular flows. Infrared radiometry provides a convenient technique for measurement of surface temperatures at the free liquid interface of falling liquid film [6J]. Large interfacial disturbances have been observed in falling film evaporators [55J] that are caused by surfactant in sea water that enhance heat transfer. Experiments [45J] are used to show that a turbulence model used by Limbeig successfully predicted evaporation coefficients with turbulent falling liquid films using a modification of the eddy diffusivity in the outer region. Reference [22J] also incorporated new gas absorption data into an improved eddy diffusivity model to demonstrate an engineering method for calculating heat transfer across a freely falling turbulent film and a turbulent film with interfacial shear due to cocurrent vapor flow. Heat transfer to an air suspension of solids flowing in a horizontal pipe is proportional to the pipe length [37J]. This fact must be kept in mind when comparing results of different investigators. Surface tension driven flow in cylindrical melt suspended between two solid rods—commercially called "floating zone melting"—is analyzed numerically [9J]. In [36J] some similarity solutions are presented for velocity and temperature profiles within the thin film of fluid that forms between a moving hot interface and a melting solid. The laser-Dopler anemometer has been successfully utilized in velocity measurements of the individual phases in two-phase, gas liquid flow in the bubbly flow regime. The results show that the slip velocity can be measured without disturbing the flow [63J].

RADIATION

Radiation in participating media

Radiative transport in emitting, absorbing and scattering non-gray media continues to attract interest.

An analytical method is proposed for solving problems of radiative transport in an absorbing and emitting medium which does not require time-consuming numerical integrations [6K]. A study of the mean beam lengths for spheres and cylinders indicates that large values of L have a smaller effect for the cylinder and only at somewhat greater optical depths. For the sphere, where the largest L is the diameter, the deviations of the ratio of mean beam length to geometric beam length from unity is smallest [23K].

A kinetic model for the interaction of diatomic molecules with non-equilibrium radiation allows rotational and vibrational relaxation at different internal temperatures [17K]. An asymptotically exact expression for radiation heat transfer through planar media of molecular gases is derived for large optical depth using an exponential band model [15K]. By introducing an emissivity correlation parameter for the water vapor emissivity, it is shown that only a single exponential is required for describing this emissivity [4K]. Calculated band absorption applied to CO and nitric oxide shows very good agreement with experimental data [8K].

The effect of axial radiation on the cartesian Graetz problem depends strongly on the properties of the boundaries. For mirror boundaries axial radiation is negligible, even at low Peclet numbers if radiation is appreciable. In the case of black boundaries, axial radiation is negligible only when radiation effects are small and the Peclet number is large [5K]. A study of simultaneous convective and radiative heat transfer in a cylindrical geometry with uniform wall temperature considering non-gray gases such as H_2O, CH_4, CO_2 and CO shows that the optically thin approximation may be used for the calculation of heat transfer with reasonable accuracy if the dimensionless path length is less than 0.4 [9K]. Calculations of the temperature profile and of the radiative and convective wall-heat fluxes for a hydrodynamically established flow of a non-gray gas in a cylinder considering laminar as well as turbulent flow are in qualitative agreement with the constant-volume heat-source case [24K]. A linearized problem of a steady one-dimensional slow flow of a gray inviscid non-heat conducting gas past a gray semi-transparent heat source is analuzed by a method of matched asymptotic expansions assuming that the magnitude of heat transfer by radiation is dominating [10K].

If the effects of coupled thermal and non-gray radiation can be separated, the number of absorption–emission bands should be irrelevant and super-position is expected to give reasonable estimates for combined conduction–radiation through multiband, planar media [14K]. In connection with the development of a barothermal gas cell for measuring small absorption coefficients it was found that sufficient heat transfer by thermal conduction from the weakly absorbing windows into the gas produces a measurable pressure rise in the gas [2K]. In a follow-up paper a photoacoustic theory is developed for cylindrical configurations assuming that bulk absorption in the solid is the mechanism by which energy is transferred from, for example, a laser beam [1K].

Geometrically thin shock layers are, in general, advantageous in reducing the radiation heat transfer to a high-speed body [7K]. Radiative heat transfer slows down the rate of decrease of the velocity of propagation of a pressure shock [19K]. The absorption coefficients for air at high temperatures and pressures ($T \geqslant 1.6 \times 10^6$ K, $p \geqslant 30$ atm) measured behind 8–12 km/s shock waves reveal values lower than those calculated using the Biberman–Norman theory [21K].

Studies of the radiation of the fuel particles in a p.f. flame show that the index of refraction and the absorption coefficients are sensitive to a change in the content of carbon in the combustible mass of the fuel [3K]. It is shown that the two-flux spherical harmonic modelling of two-dimensional radiative transfer in furnaces or combustors provides accuracy, computational simplicity and economy compared with the zone method of analysis [18K].

A simple atmospheric transmittance model for an absorbing gas is based on temperature differences and holds for monochromatic as well as polychromatic radiation. Transmittances derived from this model agree with line-by-line calculations to within 0.0031 for the cases studied [12K].

Quantitative measurements of the ratio of the IR spectral reflectance of standard sea water at near-normal incidence to the corresponding spectral reflectance of pure water at 27°C are in general agreement with earlier results obtained at large angles of incidence [16K].

A loss formula for radiation losses of curved optical fibres with constant radius of curvature is derived as an extension of the curvature-loss formula for slab wave guides [11K]. An expression derived for the fraction of incident radiation transmitted through a right angle bend in a rectangular light pipe demonstrates that light attentuation is due only to reflection losses at the walls if the launching angle is 45° [22K].

A theoretical description of the optical properties of aggregated gold films attaining modal sizes up to 1500 Å for the visible and IR range of the spectrum is in satisfactory agreement with experiments [20K]. Single-layer, gradient refractive index anti-reflection films have been developed with a reduction of the reflectance from 8% to less than 0.5% in the wavelength regime from 0.35 to 2.5 μm [13K].

Surface radiation

Monochromatic normal emissivities have been reported [10L] for gold at wavelengths between 1 and 30 μm at temperatures of 300, 79 and 6K and have been compared with predictions. Total normal emissivities for copper and silver are also included. Spectral directional emissivities of rough metal surfaces were calculated [2L] assuming a Gaussian distribution of the slope and height of the surface roughnesses and including shadowing by adjacent peaks. Results are obtained for gold and chrome.

Shape factors for radiative exchange between parallel ring sectors sharing a common centerline have been calculated [8L]. Optical projection offers a means to determine shape factors [6L].

Local and integrated hemispherical emissivities are reported [1L] for cavities in the shape of a cone and a truncated cone touching at their bases. The emissivities increase considerably as a ring shaped lid is attached to the opening of the truncated cone. A closed form solution has been presented [5L] for the radiosity at the edge of a rectangular cavity.

A previously published theory describing radiative heat transfer in packed beds of spheres with high conductivity has been verified by measurements [7L] at temperatures between 350 and 930 K. Variational techniques have been applied [3L] to radiative and convective straight fins with steady and unsteady conditions. A computer analysis treats heat transfer in a channel formed by two vertical flat plates with asymmetric heating by combined radiation and laminar free convection [4L]. Flat and wave-shaped radiant energy receptors in straight tubes are of advantage for high temperature air preheaters because they increase heat transfer by a factor between 1.48 and 2 with an increase in pressure drop by a factor between 1.6 and 3 [9L].

LIQUID METALS

Local heat-transfer coefficients and the temperature field were measured [6M] in natural convection from a horizontal cylinder to mercury under the influence of a magnetic field. Nusselt numbers were found to decrease with increasing Hartmann number. Velocity and temperature measurements by sheathed thermocouples and by an anemometer were made [9M] for free convection flow in mercury adjacent to a vertical cylinder. An expanded Rayleigh equation was used [7M] to study the behaviour of inert argon bubbles in liquid sodium under forced convection.

An analysis [4M] of the evaporation of a hemispherical bubble in nucleate boiling of liquid metals shows that a dry patch grows near the center by evaporation of the microlayer but that its effect can usually be neglected. The analysis was extended [2M] to describe the growth of the bubble and its separation. A simple theory [3M] predicts the growth rates of hemispherical bubbles in nucleate boiling of liquid metals on heated surfaces. Experiments [5M] dealing with boiling of potassium in niobium pipes at high pressure agree with previous results and broaden the range of parameters.

Precision measurements [8M] of film condensation of mercury on a nickel-plated copper surface resulted in a temperature drop from the vapor to the film surface and in condensation coefficients which vary between 1 and 0.6 depending on condensation rate and vapor pressure. Measurements [1M] of heat transfer in condensation of potassium–vapor streams indicate that at velocities close to the molecular velocity the heat transfer decreases by an order of magnitude.

MEASUREMENT TECHNIQUES

Topics of major interest in the area of measurement techniques include laser-Doppler anemometry, hot wire anemometry, flow and velocity metering, temperature measurement, thermophysical property measurement and radiation property measurement.

Atmospheric wind speeds have been remotely measured at distances up to 60 m using a dual beam laser-Doppler anemometer (LDA) and it is projected that the techniques can be used for remote wind measurements at ranges of several hundreds of meters [8P]. The effects of finite-size probe volume on LDA measurements has been investigated and corrections for the effects are proposed which brings the LDA data into good agreement with previous hot-film data [27P]. The use of transparencies based on a few simple drawings facilitates the production of Moiré fringe patterns that visually simulate the origin of many possible LDA signals and these simulations help to clarify the physical basis for these signals [16P].

The benefits that are derived from processing the photon-resolved signal of a laser velocimeter include an increased data rate, the improvement in the particle lag problem and the capability of extracting data from low signal-to-noise ratio environments [26P].

Advances in other optical measurement techniques such as holography and interferometry have been reported. Tests have been conducted on a complete photographic system for performing real-time holographic interferometry and which has the feature that the expose-process-view cycle is fully automated [43P]. A proposed method of measuring shifts of spectral lines employing a Fabry–Perot spectrometer was analytically shown to be significantly superior to existing methods using grating instruments and the method has been employed to measure the flow velocity of an argon plasma [14P]. The production rate and diameter of water drops formed at the tips of capillaries can be measured along with their free-fall velocities with an optical detector [15P]. The feasibility of an acoustical shadowgraph technique for determining turbulent properties was demonstrated successfully by using a coherent collimated acoustic beam propagating perpendicular to a two-dimensional turbulent jet [23P].

A number of papers dealt with hot wire and hot film anemometry. An artificial fluctuating velocity field has been produced with an electrodynamic shaker to test the ability of hot wire anemometers to accurately measure higher-order moments of velocity and evidence was found to suggest that a constant-temperature anemometer may be more suitable than a constant-current anemometer for measuring odd-order moments of velocity and that both types of anomemeters are in good agreement for even-order moments [21P]. Experimental studies demonstrate that major errors are encountered when trying to measure turbulent shear stress near a wall using hot wire techniques [40P]. Wall shear stresses near a stagnation point were measured for stationary and moving surfaces using a flush mounted, hot film probe. However, the response for the dynamic case proved inadequate and an alternative technique was developed in which the probe was displaced from the wall [7P]. An experimental comparison of two generally accepted methods of Reynolds stress measurement by hot wires/films and the use of fixed vs rotating probes, lead to the result that the two methods give good agreement and the choice of which to use becomes a matter of personal preference [37P].

Preliminary results indicate that the use of a water-cooled film-type sensor is promising for measuring turbulence in high-temperature gas flows [51P]. Heat-transfer measurements for a constant-temperature hot wire anemometer showed that the Nusselt number of the wire is proportional to the Reynolds number aised to an exponent whose value varies with the gas temperature [30P]. The measurement of all three mean velocity components can be made conveniently using a single hot film anemometer [17P].

A modest number of papers described measurement techniques which involve the use of Pitot probes, flow meters, and flow visualization. An improved fast-response bell type micromanometer with a Pitot tube has been developed for measuring air speeds in the range of approximately 1 m/s [4P]. A study of the behaviour of Pitot tubes in the turbulent pipe flow of a dilute polymer solution found that errors that occurred in total pressure measurements were negative and in some cases were as high as 40% [18P]. A pair of papers in the Russian literature deal with increasing the precision of flowmeters. Formulas are recommended for engineering calculations to determine the stream coefficients, position of greatest stream contraction, local resistance coefficients of orifices, and recommended lengths of straight pipe upstream of the meter [46P]. Generalized graphs are provided which permit the selection of flowmeter parameters that are optimal for given conditions and that insure the maximum measurement precision in measuring gas flow with orifice or nozzle type meters [32P]. It has been shown that the effective hydrodynamic length of flow through a jet viscometer orifice may be used to calculate the largest admissible Reynolds number for 95% approach to fully developed flow [41P]. A probe that mixes liquid nitrogen and superheated steam produces smoke for visualization studies in low speed wind tunnels [36P].

A variety of temperature measurement techniques have been reported for a wide range of temperatures. A general discussion of the measurement of temperatures below 1.5 K is presented in [5P]. The true temperatures of gray bodies, non-gray bodies with known radiation properties, and a limited set of non-gray bodies with unknown radiation properties can be determined by measuring the radiation from the bodies in four wavelength bands [24P]. The bulk temperature of a flowing polymer stream can be measured to within approximately 1°C by using a pair of sensors, one with a highly conducting and one with a poorly conducting face, placed in a plane metal wall bounding the flow [34P]. The measurement of temperature difference by means of automatic bridges with semi-conductor thermistors is discussed in [50P].

A thermometer system which uses a platinum coated quartz wire as the sensor is capable of measuring temperature fluctuations of less than 0.1 K with a frequency of 500 Hz in air flows [35P]. It has been analytically and experimentally shown that a device with a 5.3 μm dia platinum wire can be used to record temperatures which vary as rapidly as 0.05 s [45P].

The error in temperature measurement caused by the step-like movement of the mercury in a conventional mercury-in-glass thermometer can be reduced to less than 1 mK by measuring the expansion of the mercury capacitively [39P]. An analysis was conducted to estimate the error in the measurement of the temperature of a solid body or a porous material due to conduction along the sensor leads and included the effects of an arbitrary temperature distribution along the sensor length and the conduction to the external surroundings [42P].

A CO_2 laser can be used to simultaneously heat an absorbing gas and measure its temperature [28P]. Simultaneous determinations of the temperature and species concentrations of a combustion flow were achieved using laser absorption techniques [48P]. The temperature and enthalpy of high-temperature flames issuing from burners have been determined with an accuracy of 1.5% using a simple two-thermocouple probe and the predicted temperature distribution for the probe [33P].

The determination of very high heat fluxes (on the order of 10^6 W/cm^2) to surfaces can be achieved by a comparison of calculated and measured temperature–time histories of the surface [44P].

A Pirani manometer with linear response for gas pressures between 3×10^{-4} and 0.5 torr, a time constant of 20 ms, and automatic temperature compensation for room temperature variations of ± 10°C can be built from inexpensive standard electronic components [22P].

A number of devices and techniques have been described for the determination of the specific heat, thermal conductivity and viscosity of materials. Preliminary test results indicate that a newly designed closed loop calorimeter is suitable for measuring the specific heat of liquids up to pressures of 100 MPa and temperatures of 400°C [10P]. A method has been developed for simultaneously determining the thermal conductivity and specific heat of electrically nonconducting solids with an accuracy of 1% and a precision of 0.1% on samples as small as 5×7 mm [9P]. The measurement of the thermal conductivity of solids under pressure using a transient hot wire technique is aided by the use of an electronic circuit which maintains constant power to the wire [2P]. The thermal conductivity of granular substances can be measured with high precision by using a spherical probe [38P]. The minimization of measurement errors involved in a probe method of determining soil thermal conductivity requires a minimum acceptable initial measurement time [20P].

An apparatus, which is a simple modification of a capillary extrusion rheometer, provides measurements of viscosity at much lower shear rates than can be obtained with former viscometers [11P]. Measurements of the viscosity of a slurry or suspension can be achieved by using a specially designed spindle in a conventional Brookfield viscometer [47P].

An isothermal flow calorimeter is suitable for measuring heats of reaction and heats of mixing over a temperature ange of 0–70°C and a pressure range of 1–400 atm [12P].

A method which employs total heat balances on two geometrically similar objects, one with known emittance and one with unknown emittance, has been proposed as a technique for determining the emittance of materials [3P]. A system for measuring the emittance of refractory materials in vacuum for temperatures up to 3000°C in the wavelength range of 0.4–5.0 μm has been shown to be accurate to ± 0.02 for emittances above 0.50 [25P]. An IR hemi-ellipsidal mirror reflectometer has been shown to function with very tolerable errors (less than 2%) in measuring the hemispherical-directional reflectance of room temperature samples in the 2–34 μm wavelength range [49P].

A specially designed shutter-aperture section which is placed between the test specimen and the detector in an evacuated emissometer permits the elimination of errors in the emittance measurements which are introduced by the window through which the radiation exits the evacuated system [13P]. A reference black body operating at approximately 2700 K with an emittance in the range of 0.997 to 0.999 has been built using vitreous carbon for the cavity wall [31P].

Measurements of transmittance at normal incidence have been used to simultaneously determine the refractive index and thickness of a transparent film [29P]. A determination of the temperature dependence of the refractive index of transparent liquids and solids can be achieved by an interferometric examination of the material as its temperature is changed linearly with time [1P]. A method is described for the dynamic measurement of the state of polarization of a light beam [6P].

An IR field optics system has been designed that achieves the maximum flux concentration allowed by the Abbe sine inequality and provides efficient coupling to bolometer-type detectors [19P].

HEAT-TRANSFER APPLICATIONS

Heat exchangers and heat pipes

The use of heat- and mass-transfer coefficients in the design of heat- and mass-transfer equipment simplifies, in general, the analysis and has become well established [11Q]. Some examples are shown, however, in which it is better to base calculations on heat flux. A finite difference method was used to calculate [16Q] the temperature distribution and the heat flux for tubes with rectangular fins. The results are presented in diagrams in the way that the overall heat-transfer coefficient of the tube with fins is related to the heat-transfer coefficient of a smooth tube. The mass-transfer analogy was used [10Q] to measure local transfer coefficients near the third tube in a three-row fin and tube heat exchanger. Heat transfer around the second tube in a row of three tubes was measured [1Q] for spacing to diameter ratios between 1.3 and 5 at $R = 40000$. The electrochemical method was used [5Q] to obtain shell side heat-transfer coefficients in a baffled shell and tube exchanger. A relationship of the form

$$j = A\,Re^{-1} + B\,Re^{-0.5} + C$$

for Colburn's exchange coefficient gave best fit with experimental results at Reynolds numbers between 1 and 10^4. Heat transfer in wave-shaped air preheater tubes was found [9Q] to be two times that in straight tubes with a pressure loss increase of 80%.

An analysis of a large dry cooling tower [8Q] was based on spine-fin exchanger geometry. A surface heat exchanger built into the skin of an aircraft with and without longitudinal fins removes heat from a hot air stream [7Q]. An analysis [2Q] considering heat transfer between a stream of water and a surface moving normally to the mean water velocity was based on penetration theory. The results agree well with experimental ones for high water and surface velocities but differ at low velocities. Heat transfer was measured [13Q] for pseudoplastic fluids (dilute aqueous polymer solutions) in a turbine agitated vessel for the jacket and the heat-transfer coil. Heat and mass transfer in an evaporative plate-fin heat exchanger were found [4Q] considerably larger than in equivalent single phase flow. A method of calculating heat transfer with condensation from the flow of a steam–air mixture on heat exchanger tube bundles is presented [3Q]. A design example for a typical condenser and evaporator shows (12Q) the effect of fouling factors.

The energy equations for the fluid and the solid in a regenerator can be transformed into a single one by application of an equivalence principle [14Q]. Mathematical models are described for the analysis [6Q, 15Q] of the performance of thermal regenerators including the effect of fluid hold-up. This effect increases the regenerator effectiveness at small values of the dimensionless bed length.

A design parameter for assessing wicking capabilities of heat pipes was established [17Q] as a function of a wick parameter by a large number of measurements.

Aircraft and space vehicles

Heat transfer associated with space shuttle and ablation is still of great concern although there is a decline in publication activity in this field.

By studying the effects of surface temperature and Reynolds number on leeward shuttle heating it was found that the average separated-flow Stanton number for the fuselage leeward surface depends moderately on the windward-wall to free-stream total temperature ratio [1R]. Leeward heat-transfer experiments of the shuttle orbiter fuselage indicate a steep decrease of the heat-transfer rate from an attached flow value at $\phi = 90^\circ$ to a nearly constant level within the separated region [9R]. Heating rates for highly swept wing leading edges (shuttle orbiter) may be described by a Stanton number which depends on the local Reynolds number but is independent of the free-stream flow conditions and of the surface temperature [2R]. A successful spacecraft thermal design depends on an accurate determination of the net energy transport across the vehicle control surfaces which requires a calculation of the orbit averaged albedo as a function of orbit inclination, beta angle, solar declination, surface geometry and orbit altitude [14R].

Results of numerical calculations of the heat and mass transfer within ablating teflon layers are in good agreement with ablation measurements in arc jet facilities [6R]. Tungsten and molybdenum ablation modeling for re-entry compares favorably with high-and-low pressure arc jet tests, with ballistic range firings, and with sound rocket flights [12R]. Attempts to correlate the analysis with experimental data of charring ablators show that the effective thermal conductivity of char is strongly dependent on the wall heat flux [11R].

The Hypersonic Arbitrary Body Program (HABP) in conjunction with accepted, easily used heat-transfer prediction techniques gives reasonable overall agreement with experimental results and predicts the type of heating information needed to generate nominal thermal protection system weights [10R]. Extensive investigations of the heating and pressure distribution on corrugation roughened surfaces in thick supersonic and hypersonic turbulent boundary layers show that the peak heat flux is directly proportional to the Reynolds number, whereas the thin boundary-layer data are inversely proportional to the Reynold's number [3R].

Quantitative peak heating data such as those caused by interfering flow fields can be obtained using the phase change coating technique [7R]. By introducing an effective thermophysical property defined as $(k\rho c)^{\frac{1}{2}}$, the accuracy of the phase-change coating technique for estimating local heat-transfer coefficients can be substantially improved [4R].

Both the magnitude and the distribution of calculated radiative heating rates to outer planet entry probes (Jupiter, Saturn, Uranus) is strongly dependent on the atmospheric model and the free-stream conditions [17R]. The thermal design of the Viking/Mars/ Lander is based on maximum use of passive techniques and is integrated into the overall vehicle design operation [13R].

A study of cryogenic heat pipe systems for spacecrafts indicates that for special applications a solid cryogen/heat pipe/radiant cooler system provides a weight savings when compared to a two stage solid cryogenic cooler [16R]. In the Satellite Solar Power Station (SSPS) concept it is proposed to reject waste heat associated with solar energy conversion and microwave generation direct into space [5R].

The effect of preheating of solid propellants on the burning rate seems to be associated with the thermal decomposition of the propellant [18R]. Studies of the ignition dynamics for a packed bed of solid propellant grains indicate that vigorous ignition, i.e. dumping of hot exploded gases into a propellant bed within 100 μs results in extreme pressures in the bed interior [8R].

Local heat flux calculations in rocket-engine nozzle walls assuming a linear temperature distribution perpendicular to the wall surface may be substantially in error [15R]. An analysis of the process of filling vehicle-borne, high-pressure gas tanks from gas reservoirs permits a prediction of the temperature overshoot resulting from loading a fixed weight of gas to a predetermined pressure [19R].

General

Several papers were concerned with pollution in lakes, in rivers, and in the atmosphere. A computer study [15S] of the velocity and temperature field considered a rectangular reservoir with inflow at one end and outflow at the other; windshear was taken into account. One-dimensional temperature predictions [3S] in unsteady flow were applied to the Conowingo reservoir; a one-dimensional two layer model describes seasonal variation of the temperature distribution in stratified lakes [12S]. Turbulence created by wind, by buoyancy, by temperature gradients, and by solar radiation absorption was considered. The analysis was applied to a calculation of the thermocline and the temperature distribution in Cayuga Lake, New York. The thermal regime of rivers was numerically predicted

[16S] for the Mississippi River. Temperature and pollutant concentrations were calculated [22S] in urban atmospheres with prescribed emissions along the city. Numerical calculations were made for a typical Midwestern town. Data collected in Calgary show multiple-cell heat islands at street level and the effect of wind speed on the urban boundary layer [14S].

Thermal instabilities in discharging gas from a cylindrical vessel were studied [10S] with schlieren cinematography. A thermal analysis [8S] of the melting of rocks by drills was compared with experiments. Pipelines are heated by steam carrying tubes arranged between the pipeline and its insulation. Performance of this scheme was analyzed [19S]. Tables are available [1S] for the thermal conductance of air caused by radiation, conduction, and convection. The analysis [18S, 23S] of heat transfer in brakes should be helpful for the improvement of the shoes. The temperature distribution within tools was measured [11S] using powders with known melting point by establishing the boundary line between melted and unmelted powder. A sudden drop in heat transfer between the ingot and the mold has been observed and analyzed [21S] occurring when the surfaces of both separate because of shrinkage. A theoretical model for heat transfer in polymer molding [4S] results in temperature and velocity profiles. The velocity and temperature field for flow through an axisymmetric furnace with coaxial burner having a swirl number 0.5 was calculated [9S] and the results were experimentally verified. Predicted exit temperature profiles from gas turbine combustors agree well with measured ones [5S].

Results in the literature on post accident heat removal in nuclear reactors were cast into a form convenient for use [2S] and were studied experimentally [7S] by measuring heat-transfer between glycerin heated by microwave radiation to simulate the molten fuel and paraffin as a melting barrier. Heat transfer in rod bundles under emergency cooling conditions was calculated [20S] considering combined radiation and convection from the fuel rod to the steam and droplet mixture. Subcooled decompression analysis [13S] was presented for a loss of coolant accident.

Three papers [6S, 17S, 24S] considered biological heat transfer in sweating, burn injury, and in the human temporal bones.

Solar energy

The number of heat transfer related solar energy papers was approximately the same in 1976 as in the previous year. Topics of major interest among these papers include insolation, materials development, flat plate collectors, concentrating collectors, energy storage, systems studies for heating and cooling, and systems studies for central electric power generation.

The present status of knowledge of the total and spectral insolation is reviewed and an overview of the solar monitoring program of NASA is presented [25T]. A conclusion that emerges from a detailed survey of solar radiation measurement, its techniques and instrumentation, is that no single method can supply the type of information needed for the large variety of solar energy applications [26T]. It is shown that it is possible to determine an average attenuation of direct-beam radiation for a single cloud and a net transformation of direct to diffuse radiation per unit of cloud area and that mean values of these quantities make it possible to reconstruct total, direct and diffuse insolation values using standard surface observations [30T].

Two papers were published dealing with the optical properties of special materials for solar applications. Transparent heat-mirror films, which transmit solar radiation but reflect IR radiation, have been made which, when used on a solar collector, produce an effect equivalent to a selective solar absorber coating with a solat absorptance of 0.9 and an IR emittance of 0.08 [9T]. Tests and calculations indicate an increase rather than a decrease in solar absorptance of second surface mirrors at angles of incidence greater than 80° [24T].

Flat plate collector study areas that have been reported include thermal tests, performance predictions, and performance improvement efforts. A standard test procedure was proposed for determining the thermal efficiency of solar collectors [10T]. The accuracy of the tests when using the proposed method would be primarily limited by the accuracy with which the insolation could be measured. The measured thermal efficiency and evaluation of 23 flat plate collectors which differ according to absorber material, absorber coating, type of glazing material, the use of honeycomb material, and the use of vacuum are presented in reference [21T].

An analytical expression was obtained which makes it possible to calculate the water outlet temperature from a flat plate collector as a function of the insolation, temperature of surroundings, wind velocity, and water flow rate [3T]. The response times of flat plate collectors increase significantly with increases in the number of covers, the thickness of the covers, the absorber thickness, and the absorber temperature, while only small changes in response time result from large variations of the emissivity of the absorber plate [31T]. For a flat plate solar collector of the sheet-and-tube design and with a serpentine tube configuration, the heat removal factor can be expressed in terms of three dimensionless groups [1T].

A comparison of collector efficiency characteristics indicated that a collector with a noselective black absorber and a glass honeycomb core between the absorber and cover plate was markedly superior to single-glazed selective-black and double-glazed nonselective-black collectors, especially at higher collector temperatures [5T]. Experimental studies indicate that a well-designed honeycomb core will give good performance in a solar collector even with clearance gaps of 1.5 mm between the core and its coverglass and between the core and the absorber plate [8T].

Concentrating collectors have also been studied. A series of papers dealing with the optics of linear concentrators resulted from work being performed on the Compound Parabolic Concentrator (CPC). The optical performance of a CPC was described in detail [16T]. A differential equation has been derived that describes the reflector of an ideal two-dimensional radiation concentrator with an absorber of arbitrary convex shape and the equation has been solved in closed form for the special case of an absorber of circular cross section [17T]. Design procedures have been described for ideal concentrators to be used for conditions of finite sources and restricted exit angles [18T].

The operational performance of cylindrical–parabolic solar collectors was the topic of three papers. It has been predicted that the performance can be completely specified by a dimensionless temperature (ratio of the absorber operating temperature to the absorber temperature in the absence of heat removal [22T]). The performance predicted for a somewhat indealized collector agrees to within approximately 20% with measured results [7T]. The maximum concentration for a cylindrical parabolic solar collector is more than 40% higher if the shape of the absorber tube is an elliptic cylinder rather than a circular cylinder [14T].

A proposed receiver, designed to operate with one-axis tracking or linear collectors, is predicted to be able to deliver 80 and 53% of the energy incident on the receiver to a working fluid for operating temperatures of 130 and 370°C respectively [4T].

A comparison of the long-term behavior of a packed bed storage system, as predicted by complex and simplified models, indicates the simple model is adequate for analyzing reasonable gravel bed heat storage systems [11T]. Na_2SO_4 is predicted to be superior to magnetise brick, alumina brick, NaCl, KCl, $CaCl_2$ and some eutectic mixtures of inorganic salts, for use as a sensible heat storage material [28T]. The transient response of a specific heat storage configuration composed of a number of rectangular cross-sectional channels for the flowing fluid connected in parallel and separated by solid storage material is described in [20T]. The decomposition of a number of classes of salts (ammonium salts, Group IA and IIA hydroxides, carbonates, sulfates, and oxides) have been evaluated in regard to their use for storage of solar energy and a number of specific salts have been selected for more detailed consideration [29T]. An analysis of the use of adsorbent beds for energy storage indicates that they can be much smaller than non-adsorbing beds, are relatively insensitive to thermal losses, and are more suited to energy storage for drying purposes than for simple heating purposes [6T].

Solar heating and cooling systems have been investigated analytically and experimentally. The application of a simulation of solar space and water heating systems for residences resulted in a simple graphical method that architects and heating engineers can use to design economical solar heating systems [13T]. Reference [15T] describes a general method for determining the most economically desirable combination of solar gain, structural energy loss, thermal energy storage, and auxiliary energy use. A solar air conditioning plant that is based on open evaporation from a lithium chloride solution flowing on a roof has been tested [12T].

Solar-thermal electric power generation studies have been reported. A solar-thermal power system using a central receiver is predicted to be more efficient than distributed collector systems because high temperatures of the working fluid can be achieved while maintaining lower radiative and convective energy losses [27T]. To achieve this efficiency requires compact boiler and superheater designs to effectively concentrate the solar heat input and to improve system power cycle efficiency [23T]. A model of the performance of large-area solar concentrators for central receiver power plants, which was formulated using a continuum field representation of ideal heliostat arrays, established theoretical limits of performance against which realistic solar power systems can be compared [19T]. The optimum efficiency predicted for the use of flat plate collectors to generate electrical power was approximately 3.5% [2T].

PLASMA HEAT TRANSFER

Heat-transfer studies in ionized gases and in MHD channels reported in 1976 refer to fundamental investigations as well as to applications, in particular to those using electric arcs as a heat source.

A survey paper on Miscellaneous Arc Devices reviews a number of more recent publications dealing with the interaction of arcs with flow and/or magnetic fields [23U]. Time-resolved laser-Doppler measurements in high-current arc plasmas yield not only information about the time evolution of the plasma flow velocity over the arc cross section, but provide also an estimate of the spatial distribution of globular electrode material in the arc as a function of time [21U]. A method is proposed for estimating axial variations in high-current free burning, quasi-steady arcs assuming that the arc energy balance is governed by axial convection and optically thin radiation [19U]. The behaviour of laminar arcs in which radiation is negligible can be predicted by a set of equations which comprise the overall integral equations derived earlier [M. D. Cowley, *J. Phys. D: Appl. Phys.* **7**, 2218 (1974)], the core energy equation, and empirical curves relating shape factors of the arc to a non-dimensional heat flux parameter [3U]. An analysis of the instability of electric arcs burning axially in accelerated flows demonstrates a strong similarity with the instabilities in fluid jets. It seems that the source of this instability is the shear layer between the cold flow and the hot, more highly accelerated arc column [7U].

Temperature measurements in magnetically balanced cross-flow rail electrode arcs indicate that forced convection and magnetic field interaction may produce different arc shapes. Depending on the parameter setting (flow velocity and balancing magnetic field strength) straight and S-shaped arcs have been observed [1U]. Thermal and electrical conductivities of water vapor plasmas are determined for temperature intervals from 2000 to 3500 K and from 7700 to 8000 K which are of particular interest in connection with transport of reaction energy in the plasma [22U]. A reduction of anode cooling in a nitrogen plasma torch using a hollow tungsten anode increases the size of the anode root and increases its travel velocity thereby reducing the anode erosion rate. At the same time the temperature distribution within the jet becomes more uniform and the power loss to the anode increases [13U],

The dynamic behaviour of an AC arc in a laminar accelerating flow depends primarily on the product of frequency and time scale of the flow which controls the relative importance of the energy transport by thermal conduction and that by convection in the conducting core of the arc around current zero [4U]. A new method for solving the energy equation for moving-boundary AC arcs should be applicable to various types of arcs including the three-dimensional case with both radial and axial convection and the case where radiation cooling dominates [10U].

Heat transfer from a hot, dense, magnetized plasma brought into sudden contact with a cold wall is in approximate agreement with classical theory. Measurement for $T = 1.5 \times 10^6$ K, $n = 1.5 \times 10^{16}\,\mathrm{cm}^{-3}$, and $B = 0.9\,T$ reveal initial heat fluxes of approximately $3 \times 10^5\,\mathrm{W/cm^2}$ [6U]. A new method for measuring extremely high local heat fluxes to surfaces is based on a comparison of calculated and measured temperature–time histories on the rear of the surfaces exposed to these heat fluxes [16U]. The application of this method for measuring peak anode heat fluxes in 5 kA pulsed arcs using nitrogen and argon at 1 atm and various anode materials reveals peak heat fluxes in the order of $100\,\mathrm{kW/cm^2}$ [17U]. Heat transfer to a sphere in an argon plasma flow may be described by the same type of dimensionless relations pertaining to low temperature flows ($T_f < 2000$ K) provided that corresponding allowances for the flow properties are introduced [9U].

Performance data are reported of a nominal 250 kW Huels-type arc heater using hydrogen in a pressure range from 10 to 50 atm and helium in a range from 25 to 100 atm with currents ranging from 240 to 400 A. Comparison of these data with data derived from arc operation in air and computer-coded correlations permit scaling of the arc heater [15U]. Spectrometric measurements of the temperature distribution in a three-phase arc gas heater reveal substantial temperature variations over the arc chamber cross section. The bulk temperature of the heated gas, however, is in satisfactory agreement with the spectrometrically determined average temperatures [14U].

A model proposed for the calculation of the two-dimensional flow and temperature fields in an inductively coupled plasma demonstrates the existence of a magnetic pumping effect which leads to the formation of two recirculating eddies, one at each end of the induction coil. At higher gas flow rates, the downstream eddy is swept away and simultaneously there is a substantial reduction of the heat flux to the plasma confining tube [2U].

A plasma produced by a 15 A arc in argon at atmospheric pressure is not in thermal equilibrium, even on the arc axis. The electron temperature is approximately 15% higher than T_{Saha} and 30% higher than the excitation temperature of the first argon ion. This will have a significant effect on heat-transfer calculations in such plasmas [5U]. Calculations of the radiation emission coefficients of SF_6 arc plasmas show that at 1 atm line radiation can be an order of magnitude higher than continuous radiation and radiation for wavelengths > 2000 Å is less than 10% of the total radiation for temperatures exceeding 15000 K [11U]. Approximate relations describing the radiation escape factor and the line source function of a nothermal plasma slab are in satisfactory agreement with numerical results of other authors [20U]. A method of computing radiative cooling of a hydrogen plasma in a shock tube assuming quasi-isothermal radiative transfer, provides results which are in good agreement with non-isothermal calculations for a plane parallel slab if the temperature gradients are $\leqslant 300$ K/cm [18U].

The pressure work and the wall conductance can have a significant influence on the limiting, fully developed heat-transfer conditions in an MHD channel [8U]. An analysis of combined free and forced convective hydromagnetic flow through a channel shows that Hall currents exert a profound influence on the flow and heat-transfer characteristics [12U].

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