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Heat transfer—a review of 1986 literature†

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INTRODUCTION

THIS REVIEW surveys papers that have been published in the literature during 1986 covering various fields of heat transfer. The literature search was made very inclusive, however, the great number of publications made selections in some of the review sections necessary.

Several conferences were devoted to heat transfer or included heat transfer topics in their sessions during 1986. The *AIAA/ASME 4th Thermophysics and Heat Transfer Conference*, sponsored by the American Institute for Aeronautics and Astronautics and the American Society of Mechanical Engineers, was held in Boston, Massachusetts, 2–4 June 1986. Several sessions dealt with heat transfer like conduction, two-phase systems, cryogenics, convection, radiation, porous media, internal flows, others were directed towards space applications like aerodynamic heating and ablation, high temperature heat pipes, immersion cooling of microaerodynamics, melting and freezing in energy systems and processes, and thermal design of spacecraft. The papers presented at the meeting can be obtained at the AIAA Library, AIAA Technical Information Service, New York. Some are also published in the archival journals of the Institute. The *31st ASME International Gas Turbine Conference and Exhibition* was held in Düsseldorf, Federal Republic of Germany, 8–12 June 1986. Sessions on film cooling and heat transfer with rotation dealt with heat transfer and many of the others included heat transfer considerations. The 1984 Gas Turbine Award was presented to H. P. Hodson for his paper "Measurements of wake generated unsteadiness in the rotor passages of axial flow turbines". Copies of the ASME papers may be obtained through the ASME Order Department. The *Solar Thermal Technology Conference*, sponsored by the U.S. Department of Energy and Sandia National Laboratories was held in Albuquerque, New Mexico, 17–19 June 1986. Among the papers presented may be listed those given at sessions on the Sterling engine, on solar concentrators, and on energy storage. The *Eighth International Heat Transfer Conference and Exhibition* was held in San Francisco, California, 17–22 August 1986. It was organized in keynote sessions, 28 papers were presented on various topics of heat transfer. Individual papers were presented in poster sessions. The opening session included a general lecture by A. W. Trivelpiece on energy research in the U.S. Department of Energy and two plenary lectures—one by E. R. G. Eckert on "The early history of international heat transfer conferences" and one by U. Grigull on "Fahrenheit, a pioneer of exact thermometry". The 1985 Max Jakob Memorial Award and Medal was presented to Frank Kreith and the 1985 Donald Q. Kern Award to Stanley J. Green. A recognition dinner honored Warren M. Rohsenow on his 65th birthday. A professional development short course program provided the possibility to update knowledge in numerical heat transfer and fluid flow in compact heat exchangers, in augmentation of heat transfer, in advances in thermal analysis and control of aerodynamic equipment, in heat transfer in packed, agitated and fluidized beds, in recent developments in heat pipes, and in experimental methods in heat transfer. All of the papers are contained in seven hardcover copies of the proceedings available from Hemisphere Publishing Corporation, Washington, D.C. The *21st Intersociety Energy Conversion Engineering Conference*, sponsored by seven engineering societies, was held in San Diego, California, 25–29 August 1986. Among the various sessions may be mentioned those on Sterling engines, hydrogen energy, seasonal thermal storage, and nuclear energy. Copies of the proceedings may be purchased from the American Chemical Society, Department of Meetings and Divisional Activities, Washington, D.C. The *XIII International Symposium on Heat and Mass Transfer in Cryoengineering and Refrigeration* was organized by the International Centre for Heat and Mass Transfer and held in Dubrovnik, Yugoslavia, 1–5 September 1986. Each of the eight sessions started with one or two invited lectures and then presented several individual papers. The following subjects were covered: thermal insulation, heat transfer in refrigerants, heat and mass transfer in mix-

†W. E. Ibele and S. V. Patankar also contributed to the preceding reviews. By an oversight the name W. E. Ibele was omitted from the list of authors of the 1984 review and the name S. V. Patankar from the list of authors of the 1985 review.

tures, thermodynamic and thermophysical properties, freezing and melting, heat and mass transfer at very low temperatures, and cooling of superconducting devices. The majority of the papers will be published in a volume available from Hemisphere Publishing Corporation. The *ASME Winter Annual Meeting*, held in Anaheim, California, 7–12 December 1986, featured eight sessions in the field of heat transfer on topics like heat transfer aspects of fusion and fission reactors, combustion in multiphase systems and modeling of combustion systems, numerical methods in heat transfer, two-phase heat and mass transfer in the environment, heat transfer in waste heat recovery and heat rejection systems. The Karl A. Gardner Memorial Session was devoted to thermal/mechanical heat exchanger design. Preprints of the papers are available from the ASME Publications Department and many of the papers will also be published in the *Journal of Heat Transfer*. The *4th Miami International Symposium on Multi-phase Transport & Particulate Phenomena* was held in Miami Beach, Florida, 15–17 December 1986. Papers of interest to heat transfer researchers covered subjects like: modeling of multiphase transport and heat transfer formulation. Interphase transfer in vapor–liquid systems, drying, boiling and condensation, pool boiling, critical heat flux, freezing and melting, and various measurement techniques. Inquiries about reprints should be directed to the Clean Energy Research Institute, University of Miami, Corral Gables, Florida.

A number of books became available during the past year and they are listed in the references. A new journal also started publication.

HIGHLIGHTS

The following highlights illuminate areas of research which received special attention during the last year.

A considerable number of papers presented computer solutions of various heat transfer problems. Some of them appear to be mainly motivated by the capability of the equipment used.

Conduction in composite media received considerable attention with the majority considering the effect of contact resistance. Several new approaches were presented for the handling of the Stefan problem and the inverse conduction problem. Attention was also focused on conduction in materials subject to transient laser irradiation.

Channel flow studies concentrated on complex geometries, non-Newtonian flows, and the effects of buoyancy forces. *Boundary layer flows* with stagnation regions, particularly on cylinders in crossflow and over axisymmetric bodies, found attention. The reduction in the number of papers on viscous heating of high-speed vehicles and the increase in the number of papers on turbulent heat and flow modeling are noteworthy. Papers on *flows with separated regions* considered cylinders in tandem and banks of cylinders. A surprising number of papers were concerned with acoustic effects on cylinders and plates with separated regions.

Heat transfer in *fluidized beds* is one area for which our knowledge is mostly empirical. All papers except one in this area report the results of experimental studies. The opposite is true for heat transfer in *packed beds and porous media* where the majority of papers are analytical.

Noteworthy *instrumentation* developments include two papers on temperature measurement at ultra high pressure, ten papers on cryogenic temperature measurement and some on Raman scattering techniques developed for supersonic flows and flames. The majority of papers on external *natural convection* considered boundary layer flows over vertical flat plates and consist of numerical solutions to steady laminar flow problems. They include effects of temperature dependent fluid properties, viscoelastic fluids and coupling between wall conduction and adjacent convective flow.

Boiling heat transfer continues to be an active field of experimental research. Boiling of specially prepared surfaces and direct contact boiling processes were studied. Transition boiling and boiling of mixtures are topics of increasing interest. *Condensation* rates of horizontal tubes were studied extensively as well as direct contact condensation to flowing and static liquids. Promotion of dropwise condensation continues to be of interest. A number of analytical and experimental studies were concerned with *properties of materials* for specified applications. The majority of papers on *solar energy* considered the thermal performance of components such as solar collectors, solar ponds, and thermal storage systems. A few papers considered the performance of complete active solar heating and cooling systems, passively heated buildings, and solar radiation data.

Heat transfer in *thermal plasma* has been of particular interest in connection with electric arcs and arc applications.

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

Conduction, A
Channel flow, B
Boundary-layer and external flows, C
Flow with separated regions, D
Heat transfer in porous media, DP
Experimental techniques and instrumentation, E
Natural convection—internal flows, F
Natural convection—external flows, FF
Convection from rotating surfaces, G
Combined heat and mass transfer, H
Change of phase—boiling, J
Change of phase—condensation, JJ
Change of phase—freezing and melting, JM

Radiation in participating media and surface radiation, K
Numerical methods, N
Transport properties, P
Heat transfer application—heat pipes and heat exchangers, Q
Heat transfer applications—general, S
Solar energy, T
Plasma heat transfer and MHD, U.

CONDUCTION

A number of studies were published in 1986 on heat transfer in composite media and inhomogeneous materials. The applicability limits of the homogeneous property model were considered in relation to the transient thermal behavior of directional reinforced composites [6A]. It was found that in many situations the homogeneous property model may lead to significant errors. The cooling by convection of an infinite parallel-sided composite slab was solved analytically by the Wiener–Hopf technique [20A]. An equivalent inclusion method, analogous to Eshelby's method in elasticity, was proposed for solving steady-state conduction in composites [31A]. A new method based on the theory of systems was advanced for the calculation of heat flow as a function of surface temperatures in a multi-layer wall with time-dependent boundary conditions [50A]. A method was presented for obtaining the effective thermal conductivity and specific heat in composite materials with an oscillating temperature field [49A]. It was claimed that the apparent thermal conductivity for steady-state conduction is not sufficient to describe the transient behavior of an inhomogeneous medium [10A]. A numerial Laplace inversion technique was employed to calculate the one-dimensional transient conduction within laminated binary materials [56A]. The steady-state thermal behavior in a strip-heated composite slab was considered [37A]. A method was proposed for extrapolating the temperature at a point in a complex structure with a specified heating regime on the basis of experimental data obtained in other regimes [7A]. A technique for analyzing multilayer heat conduction, based on construction of appropriate coordinate systems, was formulated [39A].

The thermal contact resistance across an interface between solid layers is a difficult problem which received some attention. The last decade of work in steady-state contact heat transfer was reviewed, with 146 references [43A]. A review with 143 references considered the problem of heat transfer across contacts under mechanical load [57A]. The Fenech–Rohsenow model was used to analyze the thermal conductance of 240 pairs of uranium dioxide–Zircaloy-4 contacts as a function of contact pressure [28A]; conductance values obtained by this method were found to be lower than with the Ross and Stoute correlation, the difference being attributed to the use of average fluid thickness in the latter method. The fundamental concepts in the theory of composite media were reconsidered in the context of a temperature discontinuity between the constituents [17A]. The effect of geometry on contact conductance of contiguous, rough interfaces was analyzed [53A]. Theoretical and experimental work on rough sphere contact, with microirregularities, between air and mineral oil was reported [64A]. The heat transfer rate from a heated sphere to a matrix containing passive spheres of a different conductivity was calculated using a multipole expansion scheme [21A].

Transient conduction in a cylinder imbedded in an infinite conductive medium with contact resistance was expressed in integral form by a Laplace transform and then solved numerically [61A]. The problem of a cylindrical electrical conductor with temperature-dependent properties, and carrying an alternating current, was formulated and solved numerically [46A]. The question of how long a cylinder ought to be before being considered infinite for thermal conduction was examined [22A]. Heat transfer from a set of parallel tubes of arbitrary diameters and positions, imbedded in a semi-infinite medium, was analyzed [4A]. The steady-state temperature distribution in a circular tube with internal convection and external asymmetrical heat flux was obtained by finite Fourier transform, with Biot number as a parameter, and numerical calculation [58A]. Heat conduction in a thin circular pipe with a circumferentially moving heat source is often approximated as a flat plate problem; significant linear corrections to this approximation were obtained via an asymptotic expansion in terms of the ratio of pipe thickness to radius [48A]. The first ten eigenvalues needed for the computation of transient heat or mass diffusion in a hollow cylinder without azimuthal symmetry were calculated [25A].

Conduction in other circular bodies was analyzed in several works, including a discussion of the existence of a classical solution of a mixed third boundary value problem on a sphere [36A] and a study of steady conduction in arbitrary conical systems [11A]. For conical shells, a method was described which allows one to calculate the average temperature (through the shell thickness at a particular location) and temperature gradient directly from the theory of a Cosserat surface [54A]. The steady temperature distribution for arbitrary paraboloidal systems was investigated [12A].

An exact analytical solution for a non-linear fin problem—a rectangular fin subject to a power law-type temperature dependence—was presented [55A]. A series solution was presented for the one-dimensional temperature distribution along a straight rectangular fin with variable surface heat transfer coefficient [9A]. The optimum dimensions of annular fin assemblies were studied [18A].

The Stefan problem, or the problem of phase change with a moving boundary, was treated by several authors. The melting process in a rectangular enclosure was analyzed, with a coupling between solid-phase heat conduction and natural convection in the melt. The kinetics of the melting process were found to be significantly modified by this coupling [16A]. An integral method was presented which utilizes Galerkin functions for phase-change problems, which can accommodate problems with time-dependent temperatures at the boundary [44A]. The Backlund transformation was applied to reduce a class of moving boundary problems to a form which admits a class of exact solutions [51A]. A new method for solving the Stefan problem was proposed in which two associated conduction problems, each having fixed domains and the same boundary and initial conditions as the original problem, are introduced; each includes a moving source as a supplementary condition [60A]. It was shown that the natural sign conditions in a general Stefan-like problem are sufficient to ensure that a solution exists globally [38A].

Analytical approaches to non-linear heat equations were considered in a work which utilized Bergman-type series solutions [52A] and in another which used group theory [23A]. Two studies considered the hyperbolic heat equation which results from a finite speed of heat propagation [24A,30A].

A tabulation and numbering system for Green's functions was proposed, for rectangular coordinates with 220 different sets of boundary conditions [14A]. Approximate integral transformation techniques for difficult conduction problems were discussed [63A]. Stochastic process theory was applied to heat conduction in solids under various random conditions [35A]. A new decomposition method was proposed for approximate solutions to the heat equation [2A]. A simple method was proposed for accounting for temperature-dependent properties and boundary conditions [15A].

Steady conduction in an orthotropic plate with a foreign inclusion of arbitrary but small thickness was examined [47A]. Periodic on–off heating was contrasted with continuous heating in a numerical study [19A].

The application of laser heating in industrial processes is posing an interesting class of conduction problems, involving both optical and thermal properties of the irradiated medium as well as the intensity profile of the laser beam. An exact solution was presented for the heating of a homogeneous slab induced by time-dependent laser irradiance [26A]. A general solution was obtained for a semi-infinite two-layer system heated with a cw laser beam of either Gaussian or uniform circular intensity profile [1A]. The three-dimensional conduction equation was solved numerically for scanning cw laser-annealed multilayer structures [66A]. In the case of irradiation at high power intensities the usual assumptions made in the Fourier theory may be inadequate, as the heat flux through a given plane depends on the electron energy distribution. A model was introduced for analyzing the conduction problem by means of electron kinetic theory [70A]. An integral solution was described to deal with complicated geometries undergoing both motion and pulsed laser irradiation [45A]. While not referring specifically to lasers, a related work used Fourier transform methods to solve the problem of a heat source moving steadily over a surface [27A].

The problem of finding the temperature distribution on a surface given a set of time-varying measurements at interior points, the 'inverse' conduction problem, received considerable attention. The one-dimensional inverse problem was treated by an initial value technique which does not require iteration and which yields estimates of the surface temperature and heat flux histories [32A]. A procedure was proposed which combines two different methods, the sequential function specification method of Beck and the regularization method of Tikhonov [13A]. A generalized function-specification approach was presented for solving inverse problems which allows unified treatment of multidimensional domains in rectilinear, cylindrical and spherical coordinates [29A]. The inverse problem can be approached through Duhamel's integral, which is transformed into an equation which contains an unknown surface temperature and its derivatives [40A, 41A]. A method was proposed for two-dimensional inverse problems, involving a combination of a splitting procedure and the least squares technique [31A]. It was shown that the accuracy of an analytical solution of an inverse problem depends not only on the accuracy of the data, but also on the dimensions of the space–time domain [62A]. A transformation matrix was obtained for estimating the interface temperature distribution for a cutting tool, based on thermocouple measurements of interior points [69A]. A method was devised by determining the heat transfer coefficients during water cooling of metals, in which the temperature close to the surface was measured and used in an implicit finite difference calculation [8A]. The solution of inverse heat conduction problems with partially unknown system geometries was considered [34A].

Problems in thermoelasticity are often of interest from the heat conduction viewpoint. A sudden change in temperature produces a thermal shock in a material. The transient response of an infinitely long annular cylinder composed of two dissimilar materials, subject to a thermal shock, was investigated analytically [68A]. A general solution was obtained for the transient two-dimensional temperature and stress distributions in a thermally and elastically orthotropic slab with a rectangular boundary [67A]. An insulating half-plane sliding on the surface of a conductor generates heat due to friction; the resulting thermoelastic problem was solved numerically [5A]. A study was reported of the transient thermal and mechanical behavior of an infinite medium with a spherical cavity and a non-uniform heat supply [59A]. Calculations were presented of the temperature field in a bar of finite length, subjected to cyclic bending and unsteady thermal boundary conditions [65A].

The thermal stability of a partially insulated reactive slab was analyzed; this has an interesting application to the situation of exothermically active waste material which is in thermal equilibrium with its surroundings but is suddenly subject to a small change in surface conditions, e.g. redevelopment of land formerly used for domestic or industrial waste [33A]. The thermal stability of a Landau slab was examined under various commonly encountered boundary conditions [42A].

CHANNEL FLOW

Research in channel flow is directed towards heat transfer augmentation in complex geometries, turbulent flow, multiphase effects, and non-Newtonian behavior.

Among experimental studies pertaining to turbulent flow ref. [78B] investigates the convection of helium at supercritical pressure. Turbulent heat transfer in spirally enhanced tubes has been considered in ref. [71B]. Experiments on heat transfer and pressure drop for flow in bends of circular cross-section have been reported in refs. [16B, 74B]. Reference [73B] contains a study of a shrouded fin array. An empirical correlation for heat transfer in circular tubes has been proposed [57B]. A near-wall temperature model has been applied to channel flow [1B]. Heat transfer correlation for liquids near the critical point are given [29B]. Experimental and analytical results for an asymmetrically heated duct are reported [72B].

Turbulent pulsed flow in a duct is numerically analyzed [2B]. The influence of buoyancy effects on turbulent flow are evaluated in ref. [8B]. An indirect method for studying heat transfer in a tube has been proposed [45B]. The mass transfer in the transitional regime of a wavy channel is considered [62B]. Turbulent heat transfer in ducts of cross-shaped cross-section is numerically predicted [60B]. Simultaneous convection and radiation in a turbulent channel flow is investigated [84B]. Heat transfer augmentation due to turbulence promoters is considered [65B]. The role of the structure of turbulence in heat and mass transfer is reviewed [10B]. Predictions have been reported for turbulent inclined flow in rod bundles [3B]. Reference [63B] considers the effect of entrance configurations on tube flow heat transfer. Property variations in turbulent flow are considered in ref. [42B]. Transient heat transfer to supercritical helium is investigated in ref. [7B].

Some papers deal with new aspects of simple channel flows. Transient forced convection with a stepwise variation of wall temperature is treated in ref. [20B]. The effect of axial conduction in channel and tube flows is considered in ref. [81B]. The conjugate problem for the parallel plate channel is solved in ref. [47B]. The effect of viscous dissipation in channel and tube flows is considered in refs. [50B, 51B]. Unsteady convection in a channel is experimentally investigated [22B].

Thermal instability in a tube is considered [59B]. The effect of viscosity variation on the heat transfer in a cooled tube is studied [80B]. Mixed convection in the upward flow in a vertical pipe is investigated [76B]. An analytical solution is presented for the laminar entry region of a pipe [75B]. Mixed convection is considered for a vertical annulus in refs. [32B, 33B] and for a horizontal annulus in ref. [39B].

Steady laminar flow through an elliptic twisted pipe is investigated [44B]. Predictions have been reported for laminar inclined flow through tube banks [4B]. Forced convection with periodically varying inlet temperature is considered [19B]. Reference [38B] deals with the entrance region heat transfer for toluene. The influence of an axially varying heat transfer coefficient is described [79B]. Different mechanisms for convective enhancement in disk systems are investigated [55B]. Enhancement of mass transfer due to a wavy wall is studied in ref. [61B]. Heat transfer due to radial flow between two disks is considered [56B].

The influence of combined convection and radiation in a duct flow is described [70B]. An investigation is reported for heat transfer in corrugated tubes [30B]. Experiments are reported for heat transfer on a finned wall in a rectangular duct [52B]. For a two-dimensional bifurcation, laminar forced convection is numerically analyzed [40B]. Numerical solutions are also reported for forced convection in twisted circular-sector ducts [83B]. Temperature and velocity distributions have been obtained in a square duct [17B]. Computer simulation of a melt flow is presented [82B]. Laminar convection with chemical reactions has been considered in a rectangular duct and circular tube [12B, 13B].

Convective heat transfer under the influence of discrete heat sources is considered [35B]. Reference [58B] focuses on the effect of interwall spacing on heat transfer in a corrugated duct. Convection in a multi-passage circular pipe is studied in ref. [23B]. Heat transfer in smooth and buckled tubes is investigated [69B]. Convection studies have been reported for helically coiled rectangular ducts [36B]. Laminar heat transfer in a rotating duct is presented [49B]. Fully developed flow in plate-fin passages has been numerically analyzed [68B]. Heat transfer enhancement due to oscillatory flow in grooved channels is numerically studied [28B]. A combined experimental and analytical investigation of internally finned triangular ducts has been reported [14B]. References [53B, 54B] consider heat transfer around sharp bends in rectangular channels. Numerical results are presented for convection in triangular plate-fin ducts [5B]. Convection in an elliptic duct is discussed [24B].

The combined radiation and convection in particle-laden flows is described [46B]. Measurements have been reported for mass transfer in the model of the respiratory tract [31B]. Heat transfer to cryogenic liquid under centrifugal forces is considered [41B]. Convection in a flow past two spheres in a cylindrical tube is described in ref. [21B]. Studies have been directed towards internal cooling of turbine blades [9B, 15B].

Among non-Newtonian channel flows, power-law fluids in ducts have been studied in refs. [18B, 48B]. The viscoelastic effects have been taken into account in refs. [34B, 43B]. Heat transfer to non-isothermal non-Newtonian flows is considered in refs. [6B, 25B, 85B]. Heat transfer to highly viscous rheological flows is presented in ref. [25B]. Laminar flow in a stenosis is studied in ref. [77B].

Multiphase flow and heat transfer in channels are the subject of a number of papers [27B, 37B, 63B, 66B]. Three-dimensional modeling has been applied to two-fluid flows in elbows and bends [11B].

BOUNDARY-LAYER AND EXTERNAL FLOWS

Several studies in this category dealt with the fundamentals of convection and turbulent transport. It was shown that care is necessary when comparing data for average heat transfer coefficients due to variations with position, particularly when some of the sources for those data are experimental and some are theoretical [5C]. A numerical solution of the Falkner–Skan equation was made for a laminar boundary layer using optimization techniques [3C]. Recent developments in thermodynamics of irreversible processes were applied to obtain rapid analytical solutions in Blasius flow [59C].

Studies of fundamentals in turbulent flows include a numerical study in a turbulent free shear flow [11C] and a study of turbulent motion modeled by the inviscid two-dimensional motion of point vortices [22C]. The spectrum of the latter was close to a Kolmogorov spectrum. The evolution of the temperature field in a thermal mixing layer downstream of a temperature step in grid turbulence was studied [46C]. The data was shown not to be consistent with self-similarity although second-order quantities such as heat flux coefficient and centerline temperature variance appeared to have reached their equilibrium values. An asymptotic solution was obtained for the Euler equations in the shock layer near the stagnation line for separationless flow past a blunt body in the far wake behind another body [18C]. Measurements were made of Reynolds shear stress profiles and lateral heat flux profiles in a nearly self-preserving region of the turbulent wake of a heated circular cylinder—they were compared with calculations [8C]. The comparisons do not support the need for determining a new virtual origin, as previously suggested. Results of experiments conducted in the thermal wake behind an axisymmetric body were used to evaluate the radial profiles of different terms of the temperature fluctuation balance equation [12C]. It was shown that the relationship between dissipation and turbulent diffusion is roughly the same for the flows compared. The idea of semi-preservation in non-isothermal cascade-wake-flows was presented [17C]. It was described in terms of characteristic velocity and temperature scales. An experimental study of the temperature field in round turbulent jets showed that the rate of fluid entrainment is a strong function of nozzle design [52C].

Axisymmetric and stagnation point studies include an experimental investigation of the unsteady heat transfer on the heated cylinder and blunt body stagnation regions [56C] and supersonic flow about axisymmetric bodies [75C]. The second study showed that substantial errors may result from the use of standard formulas without allowance for streamwise wall temperature gradient effects. A numerical investigation was performed to determine the heat/mass transfer from upstream-facing blunt faces of bodies situated in a uniform flow [35C]. Unsteady laminar compressible flow with mass transfer at the stagnation point was computed for different values of parameters which characterize the unsteadiness in the free-stream velocity, the wall temperature, the mass transfer rate and the variation in gas properties [70C]. A theoretical analysis for heat transfer from axisymmetric bodies in non-Newtonian fluids was presented [58C]. Asymptotic expressions give accurate predictions with high or low Prandtl numbers. Scaling relations were derived to show the influence of ballistic coefficient and lift-to-drag ratio on heating during gliding entry into the atmosphere [66C]. The effect of massive blowing on a laminar boundary layer along the stagnation line of an infinite swept cylinder was studied, where the free-stream velocity and blowing rate vary with time [71C]. Hypersonic finite-rate chemically reacting flows over an ablating carbon surface were analyzed to study the effects of ablating carbon [62C] and the interaction of a premixed flame with the flow near the stagnation point was considered under conditions where the flame stands clear of the boundary layer and pushes the incident flow away from the body [19C]. The influence of the shape of a body in motion in a hydrogen–helium atmosphere on radiant heat transfer was numerically evaluated [38C]. Heat transfer in transitional and turbulent flows along a circular rod was computed [42C].

Several studies dealt with the fundamentals of turbulence and turbulence modeling including one which presented a cascade model of redistribution of energy and temperature fluctuations over the spectrum in two-dimensional flows [20C] and one which discussed the transformation of energy within the boundary layer [65C]. Another presented a three-parameter model of turbulence for use in heat transfer calculations [45C]. A first integral of the equation relating mean temperature and heat flux was obtained which permits relating moments of the heat flux distribution to derivatives of coefficients in the mean temperature representation within a thermal mixing layer [44C]. The structure and development of the temperature field behind a line source in grid turbulence was evaluated [64C]. Molecular diffusion and viscosity had an important influence on temperature fluctuation and, it was shown, must be specifically modeled. A solution algorithm was developed for calculation of turbulent reacting flows [69C]. Calculations were made of a confined turbulent diffusion flame.

Two papers described flows with coherent structures. In one, a three-dimensional and time-dependent model was used to study the non-linear interactions between thermal convective motions, rotation and imposed flows with vertical shear [26C]. The effects of shear on convection produce longitudinal rolls aligned with the shear flow. In a second, measurements in a buoyant plume and vortex pair formed above a heated wire were made [61C].

Management of the flow was the theme of several papers. In the first, measurements of Reynolds analogy factors were made for boundary layer flows altered by stacked arrays of large-eddy breakup devices or 'turbulence manipulators' [43C]. The data show that heat transfer is sensitive to flow history. In the second, experimental results and methods for calculating heat exchange with cavitating turbulators of various geometries were presented [7C]. Heated turbulent air jets were used to study the enhancement of convection heat transfer to the stagnation region of a circular cylinder [25C]. Results show that increases in stagnation point heat transfer are more susceptible to free-stream turbulence than indicated in earlier investigations. Temperature distributions and heat transfer rates were measured for helical ribbon impellers in vessels [57C]. A critical impeller speed for eliminating temperature gradients was established.

A series of papers included mass transfer. In one, the results of laboratory studies of the heat and mass transfer from a heated evaporating liquid into a turbulent unstably stratified impinging cold air flow were presented [74C]. A formula is presented for Stanton numbers with air over smooth and wavy surfaces. Experimental results for mass transfer at the base surface of an open cylindrical cavity and a cavity with a constricted opening (Helmholtz resonator) were presented [63C]. There were two local maxima with increasing cavity depth; the first is due to reattachment and the second may be due to fluid-dynamic oscillations. Deposition rates of submicrometer particles on ribbed surfaces were compared with empirical formulation for heat transfer under similar conditions [53C]. Caution was advised when using this technique.

Gas turbine heat transfer was the topic of the following group of papers. Time-averaged heat-flux distributions obtained for the blade of a full-stage rotating turbine were presented [13C]. In a continuation paper, a detailed description of a technique using thin-film heat flux gauges for obtaining time-resolved heat flux was given [15C]. The magnitude of the heat-flux fluctuation resulting from vane–blade interaction was large by comparison with the time-averaged heat flux. Detailed measurement of heat-flux distributions for the nozzle guide vane airfoil, the hub and tip endwalls and the blade for a low-aspect-ratio turbine stage were presented [14C]. Results were compared with results of local flat-plate prediction techniques. Heat transfer measurements were performed along a cooled flat plate with various free-stream turbulence levels, pressure gradients, and cooling intensities [54C]. Results of an experimental study of the local heat transfer on the end surface of a gas turbine stator were presented [37C]. A single similarity equation accounting for the influence of streamline curvature, three-dimensional nature of the flow, flow acceleration and flow laminarization was obtained.

Several papers dealt with fins, finned surfaces and heat exchangers. A method for a combined convection and fin conduction solution was described [21C] and heat transfer from an array of parallel longitudinal fins to a film passing through the interfin spaces was analytically and experimentally studied [32C]. Results of an experimental investigation of convective transport at the surfaces of a plane transverse fin array exposed to steady turbulent flow were presented [68C]. The effect of yaw on heat transfer from a finned circular cylinder was measured [55C] and laminar flow heat transfer was computed for a situation where fluid moves along a parallel plate channel with one wall insulated [10C].

Papers on manufacturing processes included one in which similarity solutions were developed for heat transfer on a continuously accelerated sheet extruded in an ambient fluid of lower temperature [1C]. Melt-spinning and the cooling of extruded metal plates are applications. Also, heat transfer rates occurring in the laminar boundary layer on a continuous moving surface which has arbitrary surface velocity and temperature were computed [31C] and the conjugate problem was addressed [36C]. Results of a laminar flow, micropolar boundary layer study in axial flow along a continuous moving fiber were presented [24C].

Several papers were presented which deal with heat transfer on the space shuttle and space planes [2C, 6C, 48C, 67C]. One related paper discussed the shuttle's hot-gas jets for ice suppression [60C] and another the carbon ablation on a re-entry body [30C].

Studies on fluid property variation effects included one on the influence of temperature-dependent fluid properties on laminar boundary layer wedge flows [27C] and another where a method was suggested for calculating subsonic gas flows with great temperature drops [47C]. A theoretical analysis was proposed for heat transfer from external surfaces immersed in non-Newtonian fluids where integral equations were transformed into characteristic equations which can readily be solved [50C]. An asymptotic expression was derived for a speedy estimation of heat transfer to non-Newtonian fluids [51C]. The motion of a sphere in a rarefied gas was considered focusing on the role of temperature variation in the Knudsen layer [40C]. Results show that velocity and pressure in the layer and the drag on the sphere are not sensitive to this variation. Molecular–kinetic methods were used to investigate the heat transfer on the surface of a spherical particle for arbitrary Knudsen numbers and temperature differences [23C]. An investigation of a reaction wave igniting initially cold matter, with allowance for the physical processes occurring in a completely ionized medium, was presented; electron heat conduction, radiative losses and energy transfer between electrons and ions were included [41C]. An analysis was presented for heat transfer characteristics of a thermo-micropolar fluid flowing through a channel followed by a convergent or divergent section [4C]. An increase in wall mass transfer was reported for liquid–gas flow of drag-reducing fluids [34C].

Studies of flows influenced by external effects include an experimental study on heat transfer to a single drop translating in an immiscible liquid on which an electric field was imposed [33C]. A remarkable enhancement of heat transfer was obtained due to induced circulation. Heat transfer within counter-oscillating slugs of fluid was examined where the axial heat flux pulsates at twice the base oscillation frequency [39C]. Under tuned conditions, heat transfer was orders of magnitude larger than that present in the absence of oscillations. Unsteady laminar boundary layers contiguous to self-similar flows were studied [16C]. When there is no heat transfer through the wall, the boundary layers are self-similar. The applicability and implications of the finite velocity of transport hypothesis are examined utilizing the large eddy interaction model [29C]. The model explains the manner in which turbulence relaxes following sudden curvature removal. The effect of surface roughness on adiabatic wall temperature was investigated [28C].

Among papers concerned with flow influenced by gravity was one where wave numbers were calculated for axisymmetric Rayleigh–Benard convection [9C] and one in which a continuous transformation algorithm was shown to be appropriate for the solution of a turbulent, buoyant jet [72C]. The heat transfer characteristics of laminar combined convection from an isothermal sphere were numerically evaluated [73C]. The average Nusselt number, the location of separation, the drag and the flow and temperature fields were presented. Transport processes in turbulent liquid films undergoing heating or surface evaporation were analyzed [49C]. Correlations similar to those used in conventional internal and external flows were recommended.

FLOW WITH SEPARATED REGIONS

Within this category, there were many studies dealing with cylinders in crossflow. In one, the Navier–Stokes and energy equations for laminar flow were solved by expressing temperature as well as the stream function in truncated Fourier series [8D] and, in another, the unsteady flow was numerically evaluated [21D]. Experimental results were presented for heat transfer around rectangular cylinders [7D]. The heat transfer on the rear face increases when the side face is lengthened to the point where the separated boundary layer reattaches. Heat transfer from a cylinder in crossflow was measured—a dummy cylinder and an adjacent wall were unheated and the flow near the wall was laminar, then turbulent [24D]. The clearance between the cylinder and the wall was varied. Results of an experiment of heat transfer characteristics of two elliptic cylinders placed in a tandem arrangement were presented [19D]. Their angles of attack were the same in magnitude, but opposite in sign. In a similar test, heat transfer characteristics of two elliptic cylinders in tandem were evaluated [20D]. It was found that angle of attack and separation distance were important. Mass transfer coefficients were evaluated for a cylinder in crossflow where the cylinder had a step in diameter in the center of the test section [14D]. Heat transfer rates around a circular cylinder above a plane boundary were measured [1D]. The mean Nusselt number reached a maximum when the separation distance was equal to about one cylinder radius. Experimental results were presented for heat transfer from a cylinder under cavitation condition [13D]. The heat transfer on the down-flow part of the cylinder surface almost doubled for the cavitation case over one without cavitation. The effect of a relatively high-frequency audible sound field on cylinder heat transfer augmentation was measured [1D]. Acoustic streaming was shown to augment heat transfer; a critical level of 148 db was found. In another study, it was shown that acoustic streaming increases heat transfer mainly on the speaker side with the effect depending more on the streaming velocity than on sound pressure level [11D]. The effect of sound fields on heat transfer from a flat plate having separated and reattaching flow was measured [4D]. Increasing the sound level decreased the length of the separation bubble. The effect of vibrations on local and average heat transfer was evaluated [9D, 10D]. Vibration enhances heat transfer and leads to transition at lower Reynolds number, as does free-stream turbulence. An experimental technique for obtaining local heat flux was presented and data were discussed for heat transfer from a cylinder, cylinders in tandem and cylinders in a tube bank [2D]. For tube banks, the average heat transfer coefficient became invariant by the third row. In a similar study, heat transfer over smooth bundled tubes in transverse flow was discussed [25D]. Numerical results were presented for laminar flow and heat transfer in staggered tube banks and a new expression was proposed for predicting the average heat transfer [5D]. The effects of transversal and longitudinal pitches and the effect of tube roughness were experimentally evaluated [17D, 32D]. Tube roughness has a significant effect. Measurements of heat transfer around a two-dimensional blunt body showed an order of magnitude increase across a small separation bubble, when one exists, where the leading edge joins the body [3D]. Applications include turbomachinery airfoils. Heat transfer rates in the stagnation region of the junction of a circular cylinder perpendicular to a flat plate were measured [6D]. The influence of the cylinder on the flat plate extended beyond three-fourths of a cylinder diameter. Experiments were performed to document the effects of vibration and rotation on heat transfer from spheres [15D]. The authors concluded that air velocity fluctuations and rotational movement of particles on heat transfer cannot be neglected in gas–solid two-phase flows.

Several studies dealt with an abrupt change in surface geometry which leads to separation. In one, heat transfer characteristics of forced convection over an inclined flat plate of finite width were investigated [18D]. They depend considerably on the shapes of the leading edge and the angle of attack. The influence of an unheated frontal end of a cylinder on its heat transfer in longitudinal flow was studied [27D]. Differences were found in the zone of flow separation. The effects of free-stream turbulence and of separation angle on heat transfer characteristics in the reattachment region behind a backward-facing step were investigated [16D]. The effect of turbulence varied with angle. Experimental results were presented for turbulent channel flow with an abrupt area expansion [26D]. The heat transfer characteristics were influenced by the large temperature gradient between the bubble and the main flow in the upstream separated region. A numerical study of this problem used a full Reynolds stress model for the Navier–Stokes equations and an algebraic model for the thermal fluxes [22D]. In a similar study, Mach 2.6 flow passed over a back-step—the compressible effects were documented [23D]. Heat transfer with compressible flow and separation in the presence of a step-cavity profile of the divergent part of the Laval nozzle was presented [28D]. The influence of a protrusion of the surface was measured [31D]. The recovery of equilibrium flow was not reached during the relaxation process after reattachment.

An equation presented for flow in a bubble column was used to estimate both the blending in the liquid phase and the heat transfer on heated or cooled surfaces of bubble columns [29D, 30D].

HEAT TRANSFER IN POROUS MEDIA

A very large number of papers dealt with computer solutions of buoyancy-induced flow in saturated porous media considering various geometries, boundary conditions, for Darcy flow and for conditions where inertia effects cannot be neglected. This section of heat transfer in porous media will be organized in the way that papers studying detailed transfer processes are collected in the first section whereas the following sections enumerate briefly specific geometries and boundary conditions.

Multiple solutions for buoyancy induced flow in saturated fluids are discussed in refs. [1DP, 2DP] and the path through bifurcation to chaos occurring with increasing Rayleigh number is considered in ref. [3DP]. Thermodynamic modeling [4DP] using irreversible thermodynamics establishes that Brinkman's law is justified. Effects of flow inertia are considered in ref. [5DP]. Effective heat transfer parameters developed for transient flow [6DP] are claimed to unify all previous solutions. A boundary layer approximation for natural convection in stratified porous media heated from the side [7DP] is compared with numerical calculations. Radiative and conductive heat transfer [8DP] describe heat transport in unsteady high temperature gas streams. Impulsively heated fluid streams percolated through fixed beds [9DP] spread in the form of temperature waves for air flowing through a bed of glass beads but as steepening waves in the flow of CO_2 through a bed of lead beads.

Conjugate heat transfer from vertical fins to a saturated porous medium are discussed in refs. [10DP, 11DP]. Analyses are also presented for steady and unsteady heat transfer from vertical plates [12DP, 13DP] and vertical cylinders [14DP, 14aDP]. Vertical and horizontal annuli are treated in refs. [15DP–17DP]. Analyses of vertical and horizontal channels are presented in refs. [18DP–21DP]. Free convection in an undulating porous cylinder [22DP] and the stability of natural convection flow are analyzed in refs. [22DP, 23DP] as in the free convection in a two-dimensional porous loop [24DP]. Benard convection is studied at various Prandtl numbers in refs. [25DP, 25aDP]. Geothermal applications suggested the analysis of thermally-driven shallow cavity flows [26DP]. Free boundary flow through a porous body and flow along a heated horizontal cylinder [27DP, 28DP] yielded to numerical calculations.

Much smaller is the number of papers dealing with *unsaturated porous medium*. Unsteady heat and mass transfer creates convective flow in a porous slab [29DP]. Accumulation and migration of moisture in insulations occurs by simultaneous heat and mass transfer [30DP]. An analytical paper is concerned with Soret and Dufour effects and double diffusion [31DP]. The validity of experimental models is investigated by an analysis [32DP]. Unsteady simultaneous heat and mass transfer with phase change occurs in three successive regimes [33DP]. At first the condensate is immobile and accumulates with time, then it becomes mobile generating unsteady concentration and temperature profiles, and finally the situation approaches asymptotically a quasisteady condition. The role of capillarity is demonstrated [34DP] to enhance heat transfer in partially-saturated systems by an order of magnitude. An analysis considers natural convection of gas/vapor mixtures in a horizontal rectangular channel [35DP]. Heat transfer between a granular structure and liquid 3He is studied by a microscopic calculation [36DP]. The hydrodynamic equations describing thermal convection and non-linear effects of superfluid 3He–4He mixture are derived [37DP] and two-fluid effects are calculated.

Considerably smaller is the number of *experimental investigations* which are looking again at different geometries and boundary conditions of porous media. Papers in this field deal with transient and steady conditions in coaxial vertical cylinders [38DP, 39DP], in horizontal cylinders [40DP], in stratified porous media [41DP], in complex internal geometries [42DP], adjacent to a horizontal surface submerged in a porous medium saturated with water at the density extremum [43DP]. Calculations and experiments on a horizontal annulus filled with two concentric layers of glass balls of different size [44DP] resulted in the temperature and moisture field and a relation of Nusselt number as a function of Rayleigh number. Heat transfer in a mixed particle bed formed by two sizes of glass beads was measured in ref. [45DP]. An explanation of the formation of channels in debris beads during boiling of a liquid is offered in ref. [46DP]. Dryout in a bed of inductively heated steel balls of various sizes was measured [47DP] at various pressures. The temperature distribution and the freezing front movement of liquids filling the voids between glass and aluminum spheres was measured [48DP]. A simultaneous analysis gave good agreement for the glass bed but not for the aluminum bed. The heat transfer performance of a trickle flow of gas through regularly stacked packing was measured [49DP]. The results served to develop a model based on single particle flow.

Experimental investigations dominate in the field of heat transfer in *fluidized beds* indicating the situation that no general analytic approach has yet been developed. The papers in this field deal with heat transfer to emersed horizontal tubes [50DP–52DP], with horizontal tube banks [53DP, 54DP], with vertical tubes [55DP, 56DP], and with the characteristics of vertical thermal and capacitance probes [57DP]. New experimental data of the residence time of solid particles close to submerged heating surfaces have been presented [58DP]. The following correlation for heat transfer between immersed and fluidized beds of large particles was obtained from experiments [59DP]

$$Nu = 5.95(1-\varepsilon)^{2/3} + 0.55 Ar^{0.3} Re^{0.2} Pr^{1/3}$$

in which ε indicates the porosity and Ar the Archimedes number. Wall-to-bed heat transfer measurements [60DP] resulted in data for the effective thermal conductivity and a Colburn type equation describing the heat transfer coefficient [61DP]. The results of heat transfer measurements in two- and three-phase slurry fluidized beds [62DP] demonstrated that the surface renewal model satisfactorily predicts heat transfer. Two analytic papers developed a continuum model [63DP] for heat transfer in particulate flows and a model for fluidized-bed drying of granular solids [65DP]. A correlation for the local Nusselt number as a function of Grashof number based on previously published data describes heat transfer for flowing packed particle beds in circular tubes [64DP].

EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

A method was described for linearizing the outputs of standard thermocouples, involving an analog fourth-order polynominal curve-fitting circuit [44E]. An improved design was presented for a thermocouple rake for use in combustion studies [14E]. A comparison was reported of the frequency response of intrinsic thermocouples and encapsulated, beaded thermocouples in liquid sodium flows [27E]. The distortion in the steady two-dimensional temperature field which exists around a surface thermocouple was investigated [3E]. Thermoelectric instabilities in nickel-based thermocouples in the mineral-insulated metal-sheathed format were investigated up to 1100°C [6E].

Thin-film gauges enable the measurement of surface heat transfer rates [17E]. A thin-film gauge was developed which allows measurements of heat flux fluctuations up to 100 kHz [18E]. A thin-film electrical resistance heater embedded in an isolated copper cone was used with a differential thermocouple to measure heat flux from a surface with uniform temperature [5E].

A two-color pyrometer was developed for measuring the surface temperature of metal chips formed during high-speed machining [26E], and a radiation pyrometer with optical fiber was described for measuring the grinding temperature in the surface layer of a workpiece [50E]. The temperature of microscopic areas within a head/tape interface can be measured using an infrared radiometric technique [22E]. Radiometers for measuring radiative heat fluxes in large, sooty pool fires were designed to withstand severe environments and to keep the sensing area free of soot [32E]. The accuracy of a new optical fiber thermometer was demonstrated by measuring the freezing points of gold and silver [16E]. A fiber-optic thermometer based on the change in absorption characteristics of a doped glass plate was demonstrated [21E].

Raman scattering was used to measure the translational temperature as well as the molecular velocity and static pressure of nitrogen in a supersonic wind tunnel [19E]. Pulsed Raman scattering from a turbulent hydrogen jet diffusion flame was used to determine zonal averages, intermittency, and conditional probability density functions for temperature and other quantities [37E]. A method was reported using coherent anti-Stokes Raman spectroscopy to measure temperatures in the near-wake recirculating flow of a bluff-body-stabilized diffusion flame [47E]. An interferometric optical fiber sensor was constructed using a highly birefringent monomode optical fiber sensing element, and was demonstrated for measuring furnace temperatures [25E]. Passive uhf emission was used to measure electron temperature in solid-fuel MHD generators [20E]. A review with 131 references was presented on modern developments in flow visualization [43E].

There is considerable interest in instrumentation for cryogenic heat transfer, particularly in connection with superconducting magnet applications. The stability of 25 Chinese germanium resistance thermometers on thermal cycling between 20 and 239 K was reported, along with their thermometric properties in the range 1–28 K [7E]. Another report investigated the performance of Russian germanium resistance thermometers [8E]. The properties of some RuO_2 thick-film resistors were studied for their use as thermometers at temperatures in the range 0.015–4 K and in magnetic fields up to 5 T [9E]. The resistance and magnetoresistance of thick-film chip resistors was measured in the range 0.015–80 K in magnetic fields up to 20 T [30E]. A thin-film platinum resistance thermometer was investigated for temperature measurements in the range 20–300 K in a 5 T magnetic field [24E]. A glass thermometer and a nuclear orientation thermometer were compared for operation at temperatures below 40 mK in magnetic fields up to 6 T [40E]. It was shown that for carbon resistance thermometers at very low temperatures, the temperature dependence is often well represented by a 1/3-power law [46E]. In the temperature range 77–150 K, Eu^{3+}-doped fluoride glass can be used as a thermo-optic transducer because its absorption at 2.2 μm is temperature-dependent; accuracy of 0.5 K was claimed [33E]. An apparatus was reported for measuring the thermal conductance of pressed brass contacts at liquid helium temperatures [41E]. A four-terminal a.c. bridge was designed for use with low-temperature resistance thermometers [10E].

Ultrahigh pressures present a particular challenge for temperature measurement. A thermometer based on ruby R-line luminescence was shown to be useful in diamond-anvil cells, for temperature measurements in the range 10–100 K and pressures up to 120 kbar [52E]. A rhodium +0.5% iron–chromel thermocouple pair was demonstrated for measuring temperatures in a high pressure cell: it was used in a beryllium–copper cell with pressures up to 1.5 GPa, over the temperature range 4–300 K [23E].

A simple analog thermistor thermometer, using switched bridge components chosen to keep bridge sensitivity constant, was described for temperature measurements in the range 0–100°C [38E]. A diode bridge sensor for temperatures in the range 25–100°C was fabricated and tested [1E]. Response time correlations for industrial temperature sensors were reported [12E]. A method was devised for compensating for the disturbance made by a heat flow meter by placing a separate surface heater on the meter surface [15E]. The errors in surface-mounted heat flux sensors for buildings were analyzed [48E].

In miscellaneous instrumentation developments, a platinum wire probe for measuring temperature turbulence in the atmospheric boundary layer was described [31E]; a survey of the circular and square edge effects provides the information necessary to choose the appropriate apparatus size for a measurement of thermal resistance of a specimen of insulation material of arbitrary thickness [35E]; an encapsulated thermochromic liquid crystal, in a packaging arrangement suitable for gas flows, was described for mapping local heat transfer coefficients [4E] (there was surprisingly little work on liquid crystals reported in 1986); a calorimeter was developed for the purpose of evaluating thermodynamic and kinetic properties in chemical reactions associated with manufacturing processes [45E]; and the analogy between heat and mass transfer allows for the measurement of convective heat and mass transfer coefficients based on a wet-bulb thermometer exposed to an imposed heat flux [28E]. Contact and gap resistances in extruded bi-metallic finned tubes were measured by a new technique [13E].

A number of new experimental techniques were developed for measuring properties associated with heat transfer. An apparatus was designed for measuring the thermal conductivity of high-temperature materials such as stainless steel and molybdenum, over the range 400–1100 K [36E]. The thermal conductivity of liquids was measured by means of a new hot-wire instrument [11E]. A technique was developed for measuring the thermal diffusivity in one of the layers of a two-layer sample by imposing a triangular heat-pulse, as might be obtained from an Nd-glass laser [53E]. A data-acquisition system was discussed for measuring thermal diffusivity and propagation properties of thermal waves, based on the phase shift and amplitude ratio of the temperature oscillation at two fixed points [42E]. A device for *in situ* use in solar collectors was described, which measures the mass flow–specific heat product [39E]. A laser pulse method combined with a transient calorimetric technique was developed for measuring the total hemispherical emissivity of metals; the system was demonstrated for platinum in the range 1200–1600 K [34E]. Laser-pulse calorimetry applied to determining the thermal conductivity of molten oxides at high temperature was reviewed [51E].

Finally, new experimental techniques were described for measuring the thermal conductivity of oyster shells [49E] and the conductivity of the heavy oil sands of Trinidad [29E]; and a method was described for measuring the thermal diffusivity of spherical produce [2E]. It was applied to apples, oranges and potatoes.

NATURAL CONVECTION—INTERNAL FLOWS

Buoyancy driven flows are of interest to researchers from a number of disciplines including Applied Mathematics, Physics, and Engineering (both Science and Applied). Non-linear phenomena, transformation to chaos, application to geological and astrophysical systems, as well as more mundane problems continue to draw attention as indicated by the large number of studies published each year. In the present section, attention is directed to buoyancy driven flows in enclosures. These include horizontal layers heated from below and effects in layers of finite horizontal extent; flows in two-fluid systems where one layer of fluid is superimposed on another; double diffusion;

vertical slots and other geometries where differential lateral heating is present; heat transfer from one solid body to its surroundings including concentric and eccentric cylinders; convection in porous media; thermocapillary flows; combined forced and natural (mixed) convection; and other systems as well.

In a horizontal layer heated from below, the low Rayleigh number flow has been predicted using a finite element method [85F]. Another finite element study for low Rayleigh numbers indicates the influence of Prandtl number on the flow [16F]. The stability of a layer with linear and non-linear temperature distributions was determined using a technique developed for optimal control problems [71F]. Non-linear three-dimensional instability has been analyzed for constant heat flux boundary conditions [35F]. In non-linear convection with a variable coefficient of thermal expansion square cells transport more heat than two-dimensional rolls, and rolls are unstable [98F]. A number of flows were studied for fluids with high Prandtl numbers [36F]. The onset of convection in a viscoelastic fluid depends strongly on the particular constitutive relationship that characterizes the material [100F]. New oscillatory instabilities are found which indicate the presence of blobs of hot and cold fluid circulating in convection [20F]. Asymptotic properties of a bifurcation sequence that can generate random flow modes were analyzed and indicate periodic solutions which become unstable [122F].

A numerical simulation model for turbulent flow was applied to thermal convection [121F]. Another model developed for high Rayleigh number flow predicts horizontal motion of plumes [50F]. A scalar model for turbulent energy transfer can be used to predict Nusselt number at high Rayleigh number [74F].

Laboratory experiments to simulate convection in the atmosphere indicate the dynamics of the region underneath a stable or linear stratified layer [70F]. Experimental results for high Rayleigh number unsteady turbulent convection yield correlations for the mean temperature field in terms of wall-layer scales and convection scales [2F]. A new measurement technique has been utilized [30F] to study the evolution of a time-dependent convective flow.

Using a Monte Carlo simulation the dependency of the onset time for convection to start in a suddenly heated layer has been developed [62F]. Two-dimensional rolls and hexagonal cells are found to be stable in a fluid layer with internal energy sources [99F]. An electrochemical cell, in which a porous horizontal membrane separates the fluid into two layers, has been used to simulate heating from below [55F]; at high Rayleigh number, the membrane reduces the Sherwood number [54F].

A conservative lower bound for buoyancy driven convection in bounded geometries show inconsistencies in some earlier published numerical results [87F]. Flow patterns in a rectangular container heated from below, have been studied over a range of Rayleigh numbers and Prandtl numbers [68F]. An analysis uses a realistic side wall boundary condition to show differences in the flow patterns with the horizontal extent of a container [81F]. A three-dimensional numerical solution was obtained using a k–ε model for flow in a cube heated from below and cooled on one vertical wall [93F]. The influence of lateral walls on convection with a micropolar fluid [56F] is different from that found earlier with a Newtonian fluid. An experimental study on the random oscillations in a fluid-filled cubical cavity is related to periods of solar activity [18F]. Flow visualization and heat transfer measurements have been performed for various combinations of heated and cooled vertical and horizontal surfaces in a cubical enclosure [66F].

Visualization of fluid motion in a circular cylinder heated from below shows both axisymmetric and three-dimensional motions at modest Rayleigh number [40F]. Flow in a cylindrical cavity with high frequency vibration in a zero gravity field appears in the form of two vortices [103F]. The temperature and flow distributions have been calculated for a fluid contained in a hemisphere heated from below [5F]. Another study on heat transfer in a hemisphere simulates problems following an accident in a gas cooled reactor [104F].

Measurements of velocity and temperature fluctuations in a horizontal layer with uniform volumetric energy sources compare well with a simple mixing-length analysis [61F].

Coupling of electrodynamic and buoyancy forces has a large impact on heat transfer in an enclosure [88F]. The linear stability of a dielectric fluid under the simultaneous influence of a vertical a.c. field and a vertical temperature gradient was determined using a finite difference method [3F]. The influence of a vertical magnetic field on instability in a circular cylindrical container is such that the critical Rayleigh number increases as the intensity of the magnetic field increases [78F]. Another study on the effects of a magnetic field predicts the velocity and temperature fields in the resulting flow [17F].

The interaction between two fluids, one on top of the other, when heated from below has been considered in several studies. A stability analysis for a two-layer system has been extended [96F] to different Rayleigh numbers. A perturbation method [89F] predicts the onset of flow including the influence of slight curvature around the fluid–fluid interface. Calculations [75F] of the heat transfer across two layers yield the values of the Nusselt number as a function of the Rayleigh number and other parameters. A numerical analysis [63F] includes the effects of Marangoni convection at the interface of two layers. An experimental correlation has been obtained for the heat transfer across two layers heated from below [108F].

Considerable attention has been directed toward convection with double diffusion where the density differences which create and maintain a flow are caused by two different properties of the fluid, generally temperature and composition. With non-uniform temperature and composition, diffusion of heat and mass occur simultaneously. Usually the diffusion of mass is at a much lower rate than the thermal diffusion leading to many interesting and complex phenomena. Analysis and measurement of the onset of flow in a stably stratified fluid heated from below show good agreement [59F]. Two-scale methods are employed to predict the planform in the salt-finger regime of thermohaline convection [95F]. Different mathematical approaches have been compared [84F] for predicting potentially oscillatory flows in thermohaline convection. A correlation has been developed to predict the flow in a salt-stratified fluid heated from below [15F]. The motion in a binary mixture held in a vertical layer heated from the side has been analyzed, including effects of thermodiffusion [107F]. Local heat and mass sources in double-diffusive convection influence the size of the flow cells [97F]. The successive bifurcations for convection in a double-diffusive system are extended to the development of chaos [67F]. A model predicts the transient response of a double-diffusive system, destabilized by radiation adsorption at its bottom boundary [14F]. Salinity stratification in a horizontal fluid layer has a destabilizing effect through coupling with an oscillating temperature field [120F].

Studies of convection in an inclined channel consider the influence of geometric parameters on the flow. The inclination angle has an important role in determining the flow direction in a slanted open rectangular cavity [51F]. At small angles of inclination from the horizontal, the sidewalls of a cavity give rise to secondary flows in the form of stationary transverse rolls with horizontal axes parallel to the shorter side, as opposed to the longitudinal rolls predicted for an infinite layer [80F]. A finite difference analysis for flow in an inclined layer with a partition shows the importance of the location of the partition on the flow and heat transfer characteristics [114F]. An experiment in an inclined layer with partitions shows the effect of partitions on the nature of the flow though they appear to have little influence on the heat transfer across the layer [111F]. The tilt angle and aspect ratio of an inclined layer strongly affect the Rayleigh number for the transition threshold from steady to time varying flow [94F].

Convection in the space between one solid object and a surrounding enclosure have been studied for different geometries; one is for a cylinder, often circular, inside another cylinder; another is the annulus between two spheres; and still others are for a range of different shaped objects in surrounding enclosures. The use of modeling procedures for convection in a horizontal annulus provides good agreement with earlier predictions and measurements [34F]. A special curvilinear coordinate system was developed to study the convection in annuli between concentric and eccentric horizontal cylinders [25F]. Numerical solutions for the flow in annuli between concentric and eccentric horizontal cylinders provide stream lines and isotherms, as well as, average Nusselt numbers for constant heat flux boundary conditions [43F]. An analysis shows that the Boussinesq approximation is useful even at large temperature ratios when predicting overall heat transfer with laminar convection in the annulus between horizontal concentric cylinders [79F]. The use of baffles to decrease the convective heat transfer across horizontal eccentric annuli has been studied over a range of conditions to obtain the optimum baffle orientation [11F].

Linear stability analysis has been applied to the flow in thin spherical annuli with axisymmetric disturbances; different modes of flow are found for different Prandtl number fluids [39F]. Another analysis for convection within thin spherical annuli uses a perturbation method in powers of the relative gap width [118F]. Convective flow in the region between rotating eccentric spheres has been modeled [6F].

Computations and experiments on convection in a circular horizontal cylinder with uniform energy dissipation have been perfomed over a large range of Prandtl numbers and Rayleigh numbers [82F]. Confinement of a heated horizontal cylinder by an adiabatic wall enhanced the heat transfer from the cylinder [58F]. A holographic interferometer was used [106F] to show the influence of plate inclination on heat transfer loss from a plate to a surrounding cylindrical enclosure [106F]. Measurements of the heat transfer from two heated isothermal horizontal cylinders to a surrounding enclosure provide correlations for the overall heat transfer [109F]. Unsteady natural convection from a vertical surface to a surrounding cavity was analyzed numerically [60F]. The Nusselt number for heat transfer between a cavity wall and internal fluid has been measured [123F]. A numerical study indicates the heat transfer between two concentric vertical cylinders of different heights including a case when two immiscible fluids are in the enclosure [86F].

Steady-state two-dimensional results were obtained from numerical calculations for heat transfer in a differentially heated enclosed vertical slot with a sufficiently large temperature difference to provide large variations in thermal properties [26F]. Another study considers variable properties for laminar convection in vertical channels with uniform heat flux boundary conditions [4F]. Natural circulation in a number of parallel channels with heat inputs has been studied to simulate heat transfer in a gas-cooled reactor following loss of coolant [112F]. A semi-empirical model of turbulence was employed to predict convective flow in a differentially-heated vertical layer [116F]. Numerical solutions provide heat transfer results for convection in a vertical channel with corrugated walls [38F]. Flow in a vertical wavy channel was studied using a perturbation technique [115F]. Two-dimensional convection in a rectangular cell with horizontal plate fins was determined numerically over a range of aspect ratios, Prandtl numbers, and fin parameters [91F]. A combined experimental and numerical study describes the heat transfer in a channel with a vent in the form of a slit [10F].

A numerical solution for the quasi-steady natural convection heat transfer in a vertical channel the boundary temperature of which increases linearly with time has been described [76F]. A description of the properties of quasi-steady free convection in a vertical cylinder shows the influence of a number of dimensionless parameters [27F]. Experiments in a vertical trapezoidal enclosure were carried out using water as the working fluid [65F]. The influence of the thermal boundary condition on flow and heat transfer in a vertical cylindrical annulus has been analyzed [77F].

The interaction of vaporization from a thin film running down the walls of a vertical open tube and the natural convection and heat transfer within the tube have been analyzed [24F]. In a vertical differentially heated rectangular channel filled with water near 4°C there is an upward flow on both sides of the enclosure and a downward flow in the middle [72F].

Locally measured velocity profiles were compared with numerical predictions for convection in a differentially heated rectangular enclosure with a free liquid surface [110F]. Experimental results for laminar convection in a differentially heated water filled enclosure were compared with numerical predictions [101F]. The stability of small perturbations superimposed on natural convection motions in a differentially heated fluid layer has been examined using two different numerical methods [22F]. The influence of three-dimensional boundary conditions on the temperature distribution and heat flow in a differentially heated enclosure have been measured [19F]. Experiments using a rectangular container with one vertical wall partially heated and partially cooled show two fluid cells, one above the other [41F]. A numerical algorithm has been developed to obtain three-dimensional solutions for convection in a differentially heated rectangular cavity [117F]. Velocity distributions were measured for convection in rectangular cavities with an applied horizontal temperature gradient [105F].

Numerical solutions for three-dimensional buoyancy-driven flows in differentially-heated horizontal cylinders are relevant to crystal growth by vapor transport [21F]. Surface roughness to enhance heat transfer across cubical cavities has been studied experimentally [7F]. Laser-Doppler velocimetry was used to determine the velocity distribution in a shallow differentially-heated cavity [23F]. Experiments on convection in a rectangular enclosure with a partition extending from a vertically heated wall included flow visualization using dye injection [64F]. An experiment on convection in an enclosure partially filled with glass beads provides information on heat transfer, as well as, flow visualization and temperature distribution [90F].

Thermosyphons have been of interest for many years for their practical application in modeling important flows and for their theoretical interest. Flow reversal has been predicted [73F] in a tilted toroidal thermosyphon. The heat transfer in an enclosed thermosyphon has been determined over a range of inclinations and pressures [44F]. Computation of the flow in a cavity with an internal object includes applications to two-dimensional thermosyphons [1F].

Capillary effects must be considered when there are free surfaces or fluid interfaces and a temperature difference causes a spacial variation in surface tension. These phenomena are often important in thin fluid layers, where the effective surface tension forces can be larger than those due to buoyancy producing what is called Marangoni convection. Marangoni instability in a thin horizontal fluid layer was studied for a non-linear dependence of the surface tension on temperature [31F]. The critical temperature gradient for the formation of hexagonal cells in surface tension driven flow in thin layers heated from below has been measured [69F]. An analysis of the deformation of the interface with thermocapillary convection in a rectangular cavity heated from below has been examined [102F]. Prediction of free boundaries for thermocapillary flow during the growth of a single crystal was determined using a finite element technique [33F]. The characteristics of the flow in a square cavity with simultaneous buoyancy and thermocapillary effects indicate that surface tension can either enhance or reduce the heat transfer rate depending upon the specific input parameters [13F].

Correlation of Nusselt number as a function of Rayleigh number, the radii ratio and the eccentricity has been obtained for high Rayleigh number convection in a horizontal eccentric annulus containing a saturated porous medium [49F]. Numerical calculation of linear stability limits has been described for porous media through-flow [57F]. The influence of non-Darcy effects was demonstrated in a numerical study of convection in a vertical enclosure containing a porous medium [12F].

An area of continuing interest is the study of flows with combined natural and forced convection—often called mixed convection. In these, buoyancy and externally-imposed forces interact to provide, an often rather complex, flow. A numerical study indicates that the hydrodynamic entry length in a vertical parallel plate channel is greatly increased by buoyancy effects [8F]. A related study characterizes the fully developed flow in such a channel, including the conditions under which bi-directional flow occurs [9F]. Another study for a vertical channel provides solutions for temperature and velocity with symmetric heating of the sidewalls, as well as when one plate is heated and the other is adiabatic [46F]. With large temperature differences variable fluid properties can influence the heat transfer and flow reversal in a heated vertical annulus [47F]. A shift in the location of the position of maximum temperature and a smaller Nusselt number are observed for a partially blocked heated vertical channel as compared to a smooth channel [45F].

A numerical solution for mixed convection in the entrance region of a horizontal rectangular channel shows that the Prandtl number influence is dependent on the Rayleigh number range [29F]. Calculations for mixed convection in a horizontal duct containing a power-law fluid indicate dual solutions possible with either two-cell or four-cell patterns [113F]. Experiments on mixed convection in the entrance region of horizontal and inclined rectangular channels provide a correlation of Nusselt number in terms of Rayleigh number, Reynolds number and inclination angle [83F]. A study on mixed convection in a horizontal tube surrounded by a liquid medium includes the influence of natural convection on the outer surface of the tube [32F]. Combined convection in a horizontal concentric annulus shows the effect of a rotating inner cylinder [42F]. Numerical procedures have been developed for studying convection in an inclined open cavity heated from below with a forced flow over it [52F, 53F].

Many studies on buoyancy-driven convection have a direct or indirect reference to applications; a number of these have been cited in the paragraphs above. Here we will mention a few that were aimed very closely to specific needs. The convection characteristics of the gas in a vertical narrow annual gap with its bottom open to a high temperature fluid has been evaluated using a special computer code to predict the flow in an LMFBR [119F]. An analysis shows the importance of oscillations on natural convection in a ship tank [37F]. Convection through doorways in a building has been studied to predict the influence of door height [48F]. A numerical analysis shows the convective flow around a Trombe wall, used in a solar heating system [92F]. Natural convection in liquid gas explosives has been studied to indicate its influence on ignition [28F].

NATURAL CONVECTION—EXTERNAL FLOWS

Natural convection from vertical plates continues to receive considerable attention in both experimental and theoretical studies. A non-similar transformation method was utilized to obtain solutions to flow adjacent to vertical, inclined or horizontal plates with either prescribed temperature or heat flux thermal boundary conditions [8FF]. An analysis is presented in which strong magnetic effects are presented [32FF]. Linear stability theory was used to predict the effects of temperature-dependent viscosity and buoyancy on the stability of the flow adjacent to an isothermal, vertical plate [33FF]. Experiments have been performed to investigate the flow near the maximum density of water [18FF, 29FF]. Matched asymptotic expansions and numerical methods are used to obtain solutions for a vertical heated plate with a room temperature plate attached at an arbitrary angle [25FF]. An experimental mass transfer technique to measure the thickness of a natural convection boundary layer is presented [28FF]. Two-dimensional turbulent natural convection in a vertical slot is simulated using a spectral process [12FF].

Experimental and numerical results are presented for laminar flow on a vertical plate with discrete heated elements [19FF] which includes the effect of conduction in the plate. Pure forced convection and aiding mixed convection are simulated numerically for a vertical, conducting plate fin in a micropolar fluid [23FF]. The coupling of laminar forced convection and external natural convection separated by a conducting vertical wall is considered using elliptic numerical solutions and experiments using air [26FF].

Uniform blowing or suction was modeled numerically on a vertical plate which had two sections of different temperature [20FF]. An analytical solution was obtained for the flow adjacent to a horizontal heated flat plate in which the suction velocity varies in a power law manner [2FF].

A comprehensive set of overall heat transfer correlations was presented for aiding and opposing mixed convection flow adjacent to a vertical flat plate [9FF]. An integral analysis provides results for both aiding and opposing mixed convection in which forced convection dominant and natural convection dominant regimes are identified [35FF]. Numerical solutions of transient mixed convection on a vertical plate exposed to a parallel horizontal flow were obtained which indicate that the forced flow dominates near the vertical leading edge and the natural convection dominates at large values of the horizontal coordinate [31FF]. Aiding mixed convection on a vertical plate with discrete heat sources was simulated using numerical analysis with boundary layer approximations [17FF].

Vortex instability [41FF] and wave instability [42FF] on inclined uniform heat flux plates were analyzed using linear stability theory for a fluid with a Prandtl number of 0.7 or 7. Experiments in air were performed to determine the influence of a parallel adiabatic plate located at various spacing above a heated horizontal plate [36FF] in which the maximum heat transfer occurred when the upper plate was removed. One-dimensional governing equations were solved for flow above a horizontal heated plate in water near its maximum density [11FF]. Numerical solutions were obtained for buoyant flow over an adiabatic horizontal plate with a heated strip in the center [38FF]. Investigations of combined heat and mass transfer in a salt stratified layer above a heated strip indicated that the resulting flow was a combination of Rayleigh–Benard type cells and longitudinal roll cells [5FF].

Experiments in helium showed that natural convection from a horizontal cylinder was affected by the absolute temperature involved [1FF]. A wide range of Prandtl and Rayleigh numbers were covered in a series of experiments of natural convection from a horizontal wire in a viscoelastic fluid [27FF]. The aspect ratio above which the flow from a finite length horizontal cylinder becomes two-dimensional was investigated by comparing three-dimensional numerical solutions at the midplane with corresponding two-dimensional solutions [6FF]. Heat transfer from a vertical array of cylinders in free space or enclosed between vertical parallel walls was investigated experimentally in the boundary layer regime where the Nusselt number was found to remain proportional to the Rayleigh number to the 1/4 power [34FF]. Substantially higher heat transfer rates were observed for natural convection from a horizontal finned cylinder situated in a vertical channel than when the cylinder was suspended in free space [37FF]. The effects of temperature-dependent properties were evaluated for transverse mixed convection about a horizontal cylinder using a finite difference numerical approach [3FF]. Finite element solutions were obtained of transverse mixed convection from a pair of horizontal cylinders located in the same horizontal plane [43FF]. Finite difference solutions were obtained for natural convection from a sphere with blowing or suction with either isothermal or uniform heat flux boundary conditions [24FF].

Measurements including mean velocity, local temperature, turbulence intensity and flow visualization were obtained in a buoyant jet constrained in a shallow layer [4FF]. A self-similar model and corresponding experiments were used to determine the nature of plume flows in viscous fluids that may simulate convection in the earth's mantle [15FF]. A plume adjacent to a vertical wall is studied and the results compared to a free plume [7FF]. An adiabatic wall plume adjacent to a vertical or inclined wall was modeled with a k–e–g turbulence model and the results compared to experimental data [22FF]. New correlations for the temperature distribution of a horizontal adiabatic wall situated above a plume rising from a point heat source were presented [10FF]. Wind tunnel experiments were performed in which argon gas simulated the flow of a liquefied natural gas plume flowing past a circular storage tank [21FF].

Two-dimensional finite difference solutions were obtained for natural convection about a horizontal rectangular body resting on an insulated base [39FF]. Transverse curvature effects on axisymmetric boundary layer flow of water at 4°C past a vertical cylinder were investigated [13FF]. Two theoretical studies have been made on the flow of a thermally stratified fluid through a heated, vertical open-ended cylinder [16FF, 30FF]. The flow in an infinite vertical slot is less stable when the viscosity is an exponential function of temperature than when it is constant provided $Pr > 100$ [40FF]. The optical heartbeat phenomenon is discussed [14FF] in which a laser beam propagating below a liquid free surface oscillates in intensity due to convective Benard and Marangoni instabilities.

CONVECTION FROM ROTATING SURFACES

An analysis describes the effects of Coriolis force and non-uniform temperature gradient on the Rayleigh–Benard convection in a horizontal rotating fluid [13G]. The Galerkin method was found easy to carry out and to give good agreement with numerical computations.

Steady and transient heat transfer, supported by flow visualization, was measured for natural convection in rapidly spinning containers simulating the conditions in superconducting generators with helium cooling [15G]. A correlation describing the Nusselt number for a wide range of Rayleigh and Prandtl numbers correlated the results. The convection structure, studied for Rayleigh numbers between 10^6 and 10^{11} and Taylor numbers from 10^6 to 10^{12} revealed various flow configurations in the shape of rings and grids. This grid pattern still formed around the vertical rotation axis when the vessel was inclined [2G]. Numerical experiments [8G] of steady axisymmetric flow in a heated rotating shell were performed for a non-uniform gravitational field [8G] to simulate an atmospheric circulation experiment planned for the Space Shuttle. A dielectric force is considered to simulate gravity. The flow and temperature fields in the boundary layer of heated and rotating spheres, spheroids and paraboloids were obtained [3G] for fluids with various Prandtl numbers.

Six flow regimes were obtained by a boundary layer analysis for axisymmetric flow in an internally heated fluid through a rotating channel with rectangular cross-section [12G] and the results were compared with experiments. The flow field was measured with a laser-Doppler anemometer in a rotating cylindrical cavity with radial inflow of the fluid [4G]. Heat transfer was also measured and good agreement with the Ekman layer theory was obtained. A similarity analysis of the transient temperature distribution in a partially filled rotating horizontal cylinder shows [1G] that the temperature field is a function of the Fourier number and the bubble eccentricity. A numerical calculation studied convection in the annulus between asymmetric cylinders [5G]. The inner cylinder was rotating and heated. The radius ratio was 2.6 and the eccentricity varied between 0 and 2/3. The Rayleigh number extended to 10^6, the rotating Reynolds number varied between 0 and 1120, and the Prandtl number was 0.7. Thermocapillary and centrifugal-buoyancy-driven motion was analyzed in a rapidly rotating liquid cylinder [14G] as it occurs in liquid crystal formatting. The thermocapillary effect was found to be confined to a thin layer adjacent to the surface for small Ekman number. The buoyancy effect was small but influenced the temperature field in the interior of the cylinder.

Heat transfer from rotating annular fins was studied experimentally in several papers [7G, 9G, 16G].

Local heat transfer in a round jet impinging on a rotating disk was measured [11G] for a range of rotational and jet Reynolds numbers. A finite difference calculation of laminar mixed and free convection over a rotating sphere with blowing and suction [6G] was found to be in good agreement with previous calculations. Experiments with a heated and rotating circular cylinder in crossflow, at Reynolds numbers around 4×10^4 and rotational to approach velocity ratios smaller than 2, established the fact that the location of the separation changes strongly with the cylinder wall temperature [10G].

COMBINED HEAT AND MASS TRANSFER

This section covers a number of processes which play important roles in many heat transfer applications and are often not fully understood in terms of fundamental fluid mechanics and turbulent transport. These include heat transfer from or to impinging jets, film cooling as used to protect solid surfaces over which high temperature gas flows occur, and processes similar to film cooling where mass injection from the surfaces diminishes the heat transport to the solid surface. A few papers related to drying and general combined heat and mass transfer systems are also reviewed.

Numerical analysis of the flow and heat transfer with a circular laminar jet impinging on the bottom of a cavity shows the significant influence of the spent fluid flowing from the cavity counter to the impinging jet [1H]. An impinging laminar slot jet can be used to smooth out the temperature distribution of a high temperature slab by transporting heat from one part of the slab to another [9H]. A study using a liquid jet impinging on the surface of a rotating disk, provides a correlation for the average Nusselt number as a function of three independent parameters [4H]. Measurements of the heat and mass transfer to an air jet impinging on a water surface indicate that the dimensionless transport coefficients are lower than those for impingement on a solid surface [19H].

With film cooling a fluid, usually a gas, is introduced at discrete locations on a surface over which a hot gas stream is flowing. The injected fluid (coolant) decreases the temperature in the boundary layer and thus the heat transfer to the solid surface. Numerical analysis procedures have been used to calculate the influence of film cooling using a row of injection holes [5H]; the results generally agree with available measurements. With injection of steam through one or two rows of inclined holes, a high film cooling effectiveness is found, apparently due to the relatively high specific heat of water vapor [8H]. With full coverage film cooling (in which there are a large number of injection holes distributed on the surface) there is a considerably higher heat (mass) transfer on a concave wall than on a convex surface [15H].

Several studies examine film cooling as it applies in gas turbine combustors. Measurement of the heat transfer on the approaching flow for film cooling injection through a small hole into a gas turbine combustion chamber shows the importance of the heat transfer on the approaching side of the flow [3H]. A simple model has been developed [20H] to predict the influence of slot film cooling as required to protect gas turbine combustors. In a companion study [21H] flow visualization and measurement show the importance of the flow within the slot in obtaining high film cooling effectiveness.

Several studies examine the influence of flow through a porous wall on the heat transfer to a fluid flowing over it. The influence of acceleration and mainstream turbulence on the heat transfer in a short porous tube with injection has been analyzed [11H]. The influence of variable physical properties on heat transfer in a tube with porous walls is much greater in the case of injection through the walls, than in the case of a simple mainflow [6H]. Similarity solutions have been obtained to predict the heat transfer to flow passing over a continuously moving porous plate [18H]. Combined sublimation and heat transfer to a moving permeable wall have been analyzed [7H]. Finite difference methods have been used over a range of Reynolds numbers to predict heat transfer for hypersonic viscous flow on a rotating axisymmetric porous body with fluid transpiring through the walls [13H]. Heat transfer characteristics for forced convection flow of a micropolar fluid over a porous sphere through which fluid transpires has been studied [17H].

An analytical model has been used to predict the high-intensity drying of paper adjacent to a hot surface [2H]. Another analysis predicts the mass transfer to jets used in the drying of paper [14H].

Two-phase combined heat and mass transfer has been studied for counter flowing films of liquid and gas [10H]. Heat and mass transfer to falling laminar films are analyzed to predict the absorption of water vapor in a lithium bromide solution [16H]. Computer experiments on the combined heat and mass transfer in laminar flow of a tubular polymerizer shows a strong influence on non-linear phenomena [12H].

CHANGE OF PHASE—BOILING

Nucleate boiling

The motion of liquid around a vapor bubble in saturated nucleate pool boiling was observed to agree with cited predictions and the consequent stirring effects on heat transfer agreed well with data [85J]. Bubble frequency increased but bubble departure size decreased as pressure was increased in the range of 20–129 kPa for pool boiling of liquid potassium [103J]. Numerical predictions and experimental observation addressed the behavior of a moving vapor bubble subjected to a step change in pressure [111J]. The numerical analysis was able to describe the fragmentation that occurs under some conditions as the bubble implodes. Measurements were made of the superheat at the onset of nucleate boiling in a narrow rectangular channel simulating a subchannel of a fuel element [115J]. Theory and experiment were shown to agree that small gas bubbles may persist within a liquid for extended periods of time in a stable thermodynamic state [131J]. A mathematical model of the influence of an electric field upon the departure size of nucleate boiling bubbles agreed with the experimentally observed trend of reduced bubble sizes with stronger fields and a greater liquid dielectric constant [17J]. Increasing the a.c. electric field intensity in two dielectric liquids led to increasing nucleation site density and smaller bubble departure diameter, while the electric breakdown voltage of these liquids was found to decrease when bubbles were produced at the heating surface [30J]. Liquid side mass transfer resistances were shown to be sufficient to explain reductions in heat transfer and selectivity (separation effect) of boiling binary mixtures [37J]. The augmentation of boiling heat transfer by capillary structures on the heating surface was argued to be due to the reduction of the required superheat for bubbles in equilibrium when they are in cavities [57J]. The characteristics of saturated and subcooled nucleate boiling at and near impingement of submerged jets were explored with refrigerant 113 [67J]. As heat flux was increased, boiling curves produced with different jet velocities tended to merge into a fully developed boiling asymptote which was nearly matched by the extrapolation of pool boiling curves. High-speed cinema studies of bubble departure diameter, growth rate and site density were described in the cylinder-liner cooling space of a diesel engine [107J].

Pool boiling

Measurements were made of macrolayer frequency and formation thickness with various large heat fluxes in pool boiling which compared well with analytically predicted values [11J]. The findings suggested that a large portion of the wall heat flux is transferred by conduction through the macrolayer. Pool boiling from planar surfaces in refrigerant 11 was shown to improve dramatically with surface enhancements which, unfortunately, also produced large temperature overshoot at boiling incipience [52J]. Coefficients of heat transfer generally increased slightly with the angle of inclination relative to the horizontal, up to roughly 165° for moderately low heat fluxes, while no noticeable changes occurred with inclination at higher heat fluxes. Considerable enhancement of heat transfer was also found with roughened surfaces in the transition regime [125J].

A model proposed to correlate heat fluxes to liquids boiling in porous (wick) materials was favorably compared with experimental findings for water, acetone, ethanol and refrigerants 11 and 13, and exhibited proportionality between heat flux and the square of the temperature difference [88J]. The onset of boiling was examined for wick-covered heating surfaces in pool boiling of water at pressures from 0.02 to 0.5 MPa [123J]. Flooded wicks began boiling at lower superheats than plain surfaces, greater wick thicknesses requiring smaller superheats. Pool boiling experiments with water, acetone, and a water–acetone mixture were conducted with varying depths of loose 0.2 mm steel particles on a horizontal heating surface [98J]. Particle layer enhancements of heat transfer coefficients were greatest for the pure liquids when the layer was 6–10 mm thick, while enhancements of mixture boiling, inhibited by mass transfer limitations, peaked at a depth of only 1.5 mm. Experiments with plasma-deposited particle coatings on horizontal cylinders were conducted to explore the effects of particle diameter [97J]. For all fluids tested and for all particle sizes, the enhancement of heat transfer declined with increasing heat flux. Heat transfer coefficient improvements relative to uncoated surfaces for water–alcohol and water–acetone mixtures were small or negative, especially at an intermediate particle size around 0.05 mm. Improvements tended to be larger with alcohol, acetone and their mixtures, monotonically increasing with decreasing particle size to the smallest studied, 0.035 mm.

Pulsating pressure and temperature observed in an earlier experiment with stepwise transient heating of a narrow channel open at one end were analyzed, matching the pulsation period well by modeling the bubble growth and collapse process in the fluctuating pressure field [94J]. Experiments were performed on boiling in a narrow vertical rectangular channel heated from one side with artificially injected bubbles [72J]. Heat transfer coefficients were found to vary with the inverse square root of either the period of bubble injection or, at higher heat fluxes, the period of bubble cluster motion. A model was developed to predict the extent of a dry patch produced in a narrow eccentric annulus and the corresponding temperature distribution, applicable to the crevices between tubes and tube support plates in PWR steam generators [51J]. Atmospheric and subatmospheric pressure potassium pool boiling experiments were described along with a model for the minimum heat flux required to produce an alternating dry patch boiling regime [69J]. The effects of oil in a mixture with refrigerants upon boiling heat transfer on a fine horizontal wire were explored experimentally [74J].

Flow boiling

Bounding values of liquid and vapor superficial velocities separating flow regimes in horizontal boiler tubes according to their ability to preclude the anisothermal conditions which could lead to early tube failure were analyzed and compared with data from several sources [8J]. A new correlation was proposed for forced convection boiling, based on data of water, refrigerants and ethylene glycol, for saturated and subcooled boiling in tubes and annuli [38J]. A summary of current knowledge of heat transfer in saturated flow boiling of cryogenic fluids in vertical and horizontal tubes was presented [114J]. Influences of quality, mass velocity and heat flux on flow boiling heat transfer coefficients for argon in a horizontal tube were reported [76J]. Analytical and experimental studies were reported for forced flow of He II along with the establishment of a condition for two-phase flow to occur in a transfer line [22J]. Flow boiling and CHF data were generated for mixtures of refrigerants

11 and 113 and it was determined that a linear mixing rule for composition was adequate for estimating critical quality but not heat transfer coefficients [80J]. Based on the similarity with gas–liquid adsorption processes, a model was proposed for forced convective annular evaporation (with nucleate boiling suppressed) [21J]. A Reynolds analogy approach to subcooled convective boiling was presented, permitting estimation of bubble size and hydraulic drag [7J].

Experiments with upward flowing refrigerant 113 in vertical, uniformly heated test sections with and without twisted tape inserts showed increasing augmentation of heat transfer coefficients with decreasing tape–twist ratio (twist pitch divided by twice the tube diameter) and increasing quality, pressure and heat flux [50J]. Swirled forced convection boiling heat transfer coefficients were also measured for refrigerant 12 in horizontal tubes with twisted tape inserts [2J]. Heat transfer coefficients with the inserts were found generally to exceed those for plain tubes; enhancement was greatest for small twist ratio and varied considerably with quality, heat flux and mass flow rate.

Cold experiments with air–water mixtures and heated experiments with steam–water mixtures gave evidence of a region of unstable stratified flow with moderate and low mass fluxes upward in a circular tube helically coiled around a vertical axis [27J]. Flow and heat transfer characteristics of an air–water two-phase flow were measured in helical coils with horizontal axes [128J]. Heat transfer coefficients and critical heat fluxes were found to vary considerably around the perimeter of channels carrying boiling cryogens under forced convection while simultaneously rotating around a parallel axis [101J].

Subcooled flow boiling of heptane in an annulus and past a coiled wire was investigated experimentally [77J] and compared with correlations from the literature [78J]. Crossflow boiling heat transfer on horizontal tube bundles was systematically studied by contrasting experimental results of a single heated tube alone with those for a single heated tube in an unheated tube bundle and those for a heated tube within a heated tube bundle [42J]. Heat transfer characteristics of boiling He I in aluminum plate heat exchangers with and without fins were reported [48J]. The finned surfaces displayed an advantage in film boiling while finned and unfinned surfaces had the same characteristics in nucleate boiling.

Inverted annular flow was studied with the help of adiabatic gas–water experiments and a transparent heated test section [47J]. Emphasis was placed on flow regime transition observation and modeling, producing preliminary transition criteria and droplet diameter correlations. Effects of liquid droplets on post-dryout heat transfer were found to be similar to those of solid particles in flowing gas–solid mixtures [127J], and a simplified wall temperature calculation method for post-dryout conditions was shown to reasonably approximate a lengthier numerical process presented earlier. Dispersed flow heat transfer in post-dryout conditions was reviewed in the light of recently obtained data which indicated clearly that nonequilibrium between droplets and vapor is characteristic of post-dryout flows [16J]. Several other studies of post-dryout heat transfer were reported [24J, 39J, 66J, 119J].

Transition and film boiling

Transition boiling analysis, discussed in two ways: temporal fluctuations at given locations and spatial variations at any given time, was modeled in the latter way with the goal of obtaining a universal boiling curve through recognition of both hydrodynamic effects and the surface effects of roughness and wettability [41J]. The impedance across a thin dielectric film deposited on a surface was used as an indicator of liquid–solid contact in film, transition, and nucleate boiling [20J]. Extremely small electric voidage probes were used to explore the extent, duration and frequency of liquid–solid contact at a surface with subcooled pool transition boiling of water [44J]. Theory and experiment were applied in order to understand the mechanism of transient boiling with liquid and vapor contact durations chosen as the quantitative characteristics [58J].

Experimental studies of the effects of transients and of surface thermal conductivity on the minimum heat flux condition on a small, circular, horizontal heating surface showed that, below a minimum thickness, thinner samples and quicker transients resulted in lower fluxes but no change in the superheat at the minimum heat flux point [90J]. Higher superheats and fluxes at the minimum point were induced by thicker layers of insulating PTFE on the surface. Transient film boiling and minimum heat flux were measured on a sphere in water at atmospheric pressure for various subcoolings and immersion depths [91J], suggesting a modification to the equation proposed by Hamill and Baumeister. Minimum heat fluxes for saturated pool boiling of refrigerant 113 on a horizontal surface were measured at pressures above and below atmospheric [110J], with results suggesting inclusion of the liquid–vapor density ratio in the correlation of Berenson.

An integral treatment of the two-phase boundary layer of film boiling was applied to subcooled forced convection on a flat plate [83J], forced convection on plane and axisymmetric bodies [84J], laminar pool boiling on curved surfaces [82J], and combined free and forced convection film boiling [86J, 87J]. Steady film boiling experiments were performed with a sphere immersed in a flowing stream of subcooled refrigerant 11 [96J], displaying two maxima and two minima in the boiling curve, the second pair of extrema being explained through a changed wake pattern. A model was presented for coolant vapor film growth on a hot molten sphere in a subcooled liquid coolant [56J]. The model qualitatively predicted the characteristic oscillation amplitude and time scale of experimental observations recorded elsewhere. Annular film flow boiling experiments were conducted with three fluids in a partially heated vertical channel with offset strip fins, transparent on one side to permit visual study of flow regimes [13J]. Measured coefficients of heat transfer lent credence to a postulated model. Transition and film boiling in a bottom-heated liquid-saturated porous body were studied experimentally to determine effects of the packing bead diameter for water and two refrigerants [32J]. With small particles, no maximum or minimum heat flux was observed; heat flux instead increased monotonically with heater temperature. The 'equilibrium load', a heat flux for simultaneous nucleate and film boiling on a surface, was analyzed and related to the speed of propagation of a wave by which nucleate boiling gives way to film boiling or vice versa [121J].

Critical heat flux

A 'lookup table' has been compiled for estimating critical heat flux, CHF, based upon a data base of more than 15 000 data points [36J]. The table can be employed either as a predictive tool or as a means of checking predictions of present or new correlations. An earlier theoretically based DNB prediction method was extended, by allowing for non-uniform void profiles, to void fractions up to 0.8 in both round tubes and rod bundles [132J]. A theoretically based critical heat flux prediction for low void fraction was presented which, unlike another recent predictive model, appears to be applicable to both high and low vapor densities (high and low system pressures) [130J]. The critical heat flux of subcooled boiling of water in a narrow tube was found to increase with shorter tube length and smaller inside diameter [45J]. A new dryout description, the onset of a dry sheath condition, applicable at high mass fluxes where sharp temperature excursions are not likely to be observed, was proposed as a more appropriate limit for PWR operation [35J].

Limiting heat loads were explored for water, ammonia, and three fluorocarbon refrigerants inside a vertical heated tube bundle of a natural circulation system [65J]. Flow visualizations of regimes of natural convection near critical heat flux in horizontal annular channels were described [59J]. Dryout at low heat flux, induced by flow excursions in natural convection boiling was studied, leading to an approximate, flow regime dependent, limit of safe operating heat flux [55J].

A method was proposed for determining, for any fluid, the saturated liquid pressure which will permit the largest peak nucleate boiling heat flux [113J]. It was further stated that the same pressure condition should permit the largest minimum heat flux for film boiling. In an experimental study of two-phase gas–water flow through vertical U and inverted U bends, the inverted U was shown to accommodate higher gas fluxes and lower water fluxes without large temperature rises, consistent with flow visualizations performed in transparent, adiabatic bends [118J]. Three different characteristic regimes of critical heat flux were observed for an impinging jet on a heated disk [73J], and correlations for each were developed. Critical heat flux on a horizontal cylinder with upward subcooled and low quality two-phase crossflow was measured for refrigerant 113 at 2 and 4 atm [49J]. Critical heat flux decreased linearly as quality increased up to roughly 10%, beyond which a flow regime change rendered critical heat fluxes invariant with quality. Uncovered bundle high pressure boil-off experiments yielded two modes of results; low power boil-off, for which existing steam cooling heat transfer correlations gave good predictions, and high power boil-off, for which modification had to be made to correct correlations for larger droplet cooling effects [62J].

The pressure dependence of dryout heat flux in an inductively (volumetrically) heated bed of particles was explored, displaying a monotonic increase of dryout heat flux with pressure and with particle size [70J]. Free beds of 1 mm particles allowed greater heat fluxes than constrained beds, especially at near-atmospheric pressure. Experiments and a semi-theoretical model dealt with the effects upon dryout at a horizontal surface in pool boiling of particles light enough to be suspended by turbulence [14J]. Under some heat flux and particle load conditions, a decrease in heat flux induced dryout. The dryout of downward facing surfaces in debris beds was also explored [93J].

Reactor applications

Thermo-hydraulic instability as a consequence of vapor blockage was studied with refrigerant 113 in a vertical N-shaped boiling channel with an adiabatic bypass [4J]. Two models, one of them linear, were proposed for density wave instability in parallel boiling channels [5J]. Experimental observations of such instabilities were compared [6J] for two heating methods; electrically and with hot water to stimulate conditions of LMFBR steam generators. Density wave instability thresholds were explored in a liquid sodium heated system [28J] and results contrasted with correlations. Instability thresholds predicted using a linear analysis based on a two-fluid model compared favorably with some existing data from water–steam and refrigerant 113 experiments [23J]. New approaches were presented for the analysis of instability in boiling systems [64J]. Elaboration upon an earlier method of stability analysis led to a simple method for predicting oscillation frequency and stability threshold for density wave oscillations [81J]. Coolant and fuel dynamics of a BWR were coupled in a closed form model for stability analysis of density wave oscillations [100J].

Measurements of disturbance waves in heated steam–water annular two-phase flow and in comparable adiabatic air–water flows demonstrated less pronounced and longer-tailed waves in the boiling flow as well as greater scatter of propagation velocities [79J]. The mean period of dryout point fluctuations was shown to be related to the characteristics of the dryout point location and the relationship was demonstrated with data for refrigerant 12 in a horizontal serpentine evaporator [10J]. A frequency response model of boiling flow systems was illustrated, employing a more convenient computation technique which compared well with experimental findings [106J].

In an experimental study of upward steam flow effects upon PWR reflood quenching [1J] it was determined that top-down quench velocity was delayed more by steam upflow when rod surface temperature was low and water flow rate was small. A parametric numerical study performed with a two-dimensional heat conduction code [12J] examined the effects of cladding properties and initial cladding and coolant conditions upon rewetting velocities with given channel thermo-hydraulics. Rewetting experiments with refrigerant 12 at low flow rates were reported [34J]. Experiments were conducted to evaluate the effects of oscillatory coolant injection on quench front motion and liquid carryover in reflooding [92J]. Oscillation appeared to induce initially larger but eventually smaller quench velocities; overall the quench location was related to accumulated liquid inventory in the same way in both steady and oscillatory injections. It was shown [129J] that the heat flux to vertical surfaces during bottom reflooding transients can be approximated by the wetted area heat fluxes of steady transition boiling. Trial application of the two-fluid model simulation code, SABENA, to a low heat flux sodium boiling experiment was described [89J]. A simple model was described for the transient heating and steady boiling of a solution of fissile material, applicable to accident analysis of nuclear fuel reprocessing systems [108J].

Droplet evaporation

A numerical analysis which agreed well with experimental findings suggested that increases in aspect ratio of spheroids increased drag coefficients at low Reynolds numbers but reduced drag coefficients at Reynolds numbers greater than 50, while average heat and mass fluxes showed a monotonic decline with increasing aspect ratio [19J]. Numerical estimates were made of conjugate unsteady heat transfer from spherical droplets and particles at low Reynolds number with equal thermal diffusivities of the two phases [95J]. A numerically efficient formulation of transient multicomponent droplet vaporization suitable for use in combustion spray analysis was developed and confirmed [124J]. Theoretical variations of drop size with time during evaporation in a vapor–gas mixture were presented for drops of constant temperature and drops warmed by the surrounding gas [53J]. In the latter case, the droplet may initially grow in size due to condensation. Theoretical treatments of instantaneous heat transfer coefficients for condensing two-phase bubbles and total evaporating time of a two-phase drop compared well with experimental data [104J]. Data were obtained for instantaneous growth rate, rise velocity, and heat transfer coefficient of butane droplets evaporating in water [71J]. Drops falling through a gas into a liquid were observed to entrain gas bubbles [25J], having implications for a mechanism of secondary nucleation. Flow and heat transfer characteristics were explored as refrigerant 113 boiled upon injection into flowing hot water [31J]. Photographic studies of high temperature liquid drops falling into volatile liquids displayed very uneven vapor bubble surfaces and four types of pressure–time behaviors [43J].

Liquid drop suspension on an air cushion was examined as an analog of Leidenfrost boiling, leading to a mathematical model which very closely predicted the shape of air-suspended drops and which suggested that the Leidenfrost temperature is a decreasing function of drop volume [33J]. Experiments were reported with subatmospheric pressure droplet evaporation on a surface at and above the Leidenfrost temperature [120J]. Analysis was presented of the main trends in heat and mass transfer during suspension of liquid spheroids above heated or gas permeated surfaces [63J]. Experiments were performed to compare the bubble initiation characteristics of superheated water droplets in contact with four different solid materials [116J]. The frequency of production of critical nuclei was shown to increase with a decrease in the wettability of the surface. Droplet velocity was determined to directly influence non-steady heat transfer in drop cooling of a surface, being proportional to the evaporated mass fraction of the drop [68J]. Cool liquid drops striking the surface of molten tin displayed a splash phenomenon which did not occur upon striking molten salts [117J].

Flashing and other evaporative processes

Experiments were described and correlations presented for evaporative air and water flow over a horizontal tube [105J]. Analysis and experiment suggested that heat transfer coefficients were not substantially enhanced by evaporation from a liquid surface unless other sources of heat input to the liquid were overlooked [61J]. Condensation of some of the diffusing vapor was found to stimulate the evaporation of a heated, but not boiling, liquid film into a saturated stream [3J]. Rates of evaporation of water and of toluene from a partially filled cylindrical cavity in the lower wall of a rectangular air flow channel were found to exhibit a maximum when the liquid level was roughly one half cavity diameter below the plane of the duct wall [102J]. Evaporation in film flows was examined [15J, 18J, 99J]. Conjugate evaporation from a falling film, diffusion through a non-condensable gas and film condensation on a cooler surface was analyzed using the local similar technique [26J].

Models of dynamic and thermal behavior of hot gas bubbles discharged into water were discussed [75J]. Theory and experiment were applied to the growth of bubbles in rapidly decompressed bodies of uniform temperature water [122J]. Approximate methods of determining heat flux to a growing vapor bubble from a surrounding superheated liquid were presented and compared with a numerical computation method [60J]. Heterogeneous nucleation at surfaces under decompression was modelled, based on an analysis of subcooled nucleate boiling [109J]. Experiments demonstrated that a surface instability near the limit of superheat, responsible for large heat and mass fluxes of vapor explosions, was suppressed by increased ambient pressure [29J].

The binary mutual diffusion coefficient was shown theoretically to vanish in a critical state of a binary mixture [126J]. Kinetic theory analysis was applied to unsteady evaporation [112J]. The 'paradox' that slow evaporation/condensation between two parallel liquid surfaces at unequal temperatures can result in a vapor temperature profile opposed to the applied temperature difference was shown not to violate principles of non-equilibrium thermodynamics [40J]. A review of the effects of monolayers on the evaporation of liquids showed that attempts to predict associated resistance values have not been generally successful [9J]. Rates of evaporation and composition of vapors emanating from stirred subatmospheric evaporating binary mixtures were measured and modeled incorporating convection and diffusion in the near-surface liquid [46J]. A previously proposed method of calculating mass transfer in multicomponent two-phase systems has been extended to include convective diffusion and heat transfer [54J].

CHANGE OF PHASE—CONDENSATION

An analytical expression was presented for laminar liquid film flow in the thermal entry region down inner or outer walls of a vertical cylindrical tube [40JJ]. Simple relations were developed for heat transfer from a horizontal smooth tube to a laminar falling film [31JJ], corroborating a much earlier recommendation. A theoretical study was reported of conjugate heat transfer from a condensing fluid on one side of a vertical wall to another fluid in natural convection on the other side [36JJ]. Conjugate film condensation and natural convection at the interface between a porous substance and an open space were analyzed for both condensation in the free space and condensation in the porous material [37JJ]. Two simpler alternatives were presented and contrasted with the more elaborate solution of the conjugate heat transfer problem of condensation on a finned surface, showing satisfactory agreement [1JJ].

Experimental results were presented for condensation of nearly stationary vapor on finned tube bundles and mechanisms of condensate irrigation were identified [17JJ]. An equation was presented correlating data for condensation on horizontal tube bundles for both steam and refrigerant 21 [12JJ]. Travelling waves appearing on the underside of horizontal condenser tubes were investigated [4JJ]. Experiments with condensation of nearly motionless vapor upon single horizontal cylinders of various diameters showed that condensate flow waves, which substantially enhance heat transfer coefficients relative to the Nusselt theory, occur on cylinders of all diameters [16JJ]. The effect of spacing of 1 mm thick, 1 mm high fins upon film condensation on horizontal 19 mm diameter tubes was measured for pure steam condensing at atmospheric and subatmospheric pressures [50JJ]. Maximum enhancement of heat transfer occurred with a spacing of 1.5 mm between fins.

An analytical treatment of film condensation of saturated and superheated binary vapor mixtures on a vertical plate showed that buoyant forces have appreciable influence and that vapor temperatures are strongly affected by the diffusion flux toward the liquid vapor interface [27JJ]. Experiments showed that drainage discs considerably enhanced condensation heat transfer with steam condensing at 1 atm on a vertical fluted tube [18JJ]. Optimal spacing of these discs was 50–100 mm for heat fluxes of 60–100 kW m^{-2}. Analysis and experiments were conducted with condensation on downward facing horizontal surfaces with and without porous drainage strips [23JJ]. Finned surfaces had heat transfer coefficients improved by factors up to 9 and 12, respectively, for refrigerant 113 and methanol with the drainage strips. In a brief review of laminar film condensation, it was argued that this basic phenomenon represents an important benchmark for numerical heat transfer and fluid mechanics modeling [11JJ].

Analysis suggested that forced downflow of vapor condensing over a vertical array of horizontal tubes suffers a greater reduction in heat transfer coefficient due to condensate inundation than gravity-controlled vapor flow over the same geometric configuration [13JJ]. The effects of downward vapor velocity were studied for film condensation on a horizontal tube in crossflow [22JJ]. Condensate film was observed to undergo transitions from a smooth surface to two- and then three-dimensional waves as vapor velocity increased.

An integral method, analyzing the two-phase boundary layer flow in laminar film condensation was presented [32JJ] which allowed for finite vapor density and viscosity and accounted for inertia and convection terms. The method may be extended to axisymmetric bodies. Condensing heat and mass transfer were studied for laminar and turbulent saturated vapor–gas flows on a flat plate with negligible accumulation of condensed liquid [29JJ]. The effects of composition of mixtures of refrigerants 12 and 22 during forced convective condensation inside a horizontal tube were measured [45JJ]. The mist-annular flow transition in high mass flux condensation in tubes was examined with the conclusions that a modified Weber number could discriminate between the two flow regimes, with mist flow present for Weber numbers greater than 30 [41JJ]. A mist flow heat transfer correlation was also proposed from this study. Condensation of vapor on a co-flowing liquid in an adiabatic converging duct was analyzed and compared with experimental results [28JJ]. Motivation was the heating of scale-producing fluids at free surfaces.

Heat transfer coefficients were measured for dropwise condensation of steam at pressures ranging from atmospheric down to 1 kPa [19JJ]. Nucleation site density appeared to be affected by surface physicochemical condition, and not directly by surface roughness. Although heat transfer coefficients of low pressure steam condensing dropwise on gold and chromium surfaces were nearly the same, measured droplet size distributions were markedly different, with population of the droplets on the chromium surface falling off sharply below 7 μm [20JJ]. A model of dropwise condensation was presented based upon the assumption of existence of a smallest droplet nucleation radius [52JJ]. Microscopic observation and light scattering experiments [26JJ] on 'breath figures', patterns formed when a vapor condensed to liquid on a cold surface, displayed remarkable droplet size uniformity for periods less than 300 s, radius growth between coalescences proportional to time to the power 0.23, and overall radius growth (with coalescence) proportional to time to the power 0.75. The endurance and effectiveness of many organic coatings for promoting dropwise condensation were determined for specimens observed in excess of 12 000 h [30JJ]. The sweeping effect of falling drops in dropwise condensation was explored [7JJ], providing a mechanistic explanation of observed trends of heat transfer coefficient variations with heat flux and with surface length. Dropwise condensation on a horizontal tube was modeled and measured and the predictions compared favorably with experimental results [24JJ], showing heat transfer coefficients increasing with tube diameter at low heat fluxes, independent of diameter at higher fluxes. Dropwise condensation curves and drop to filmwise transition were measured for several fluids on a copper surface treated with an agent to promote dropwise condensation [47JJ]. Experiments performed with a small cooled surface with various patterns of gold coatings to promote dropwise condensation demonstrated that mixed surfaces with dropwise and filmwise condensation taking place side by side could provide greater heat fluxes than totally dropwise condensing surfaces [51JJ].

Experiments with condensing jets of low void fraction mixtures of carbon dioxide in water entering still bodies of water were modeled in three ways; of these, only a stochastic, separated-flow analysis including finite transport rates and bubble/turbulence interactions provided reasonable agreement with measurements [43JJ]. Experiments with steam condensing on turbulent subcooled water free of bulk flow and nearly free of surface waves yielded a correlation of the condensation coefficient proportional to the r.m.s. value of the turbulent velocity [42JJ]. In the same apparatus, unstable short high intensity bursts of condensation were observed when a threshold value of turbulence intensity of the liquid was exceeded [8JJ]. Direct contact condensation of stagnant saturated steam on a horizontal flat surface of slowly moving water was studied [6JJ] while varying liquid flow rates and steam and liquid temperatures. The liquid flow rate had greatest influence on the measured heat transfer coefficients. Forced convection within a BWR containment was modeled for prediction of environmental temperature response during a postulated loss of coolant accident [5JJ]. Diffusion limited heat transfer was assumed and results agreed with experimental findings. Experimentally and analytically, thresholds of pool water subcooling were evaluated that permit induction of pressure oscillations as a steam jet discharges into the pool [2JJ]. Greater subcooling is required to allow higher frequency, chugging oscillations while lower subcooling permits low frequency bubbling. The condensation of vapor bubbles detaching from a surface producing transition boiling in subcooled water was observed and modeled [25JJ]. The 'disappearance velocity' defined as the ratio of initial bubble diameter to collapse time, was proportional to the initial growth velocity of the bubble, the square of the wall heat flux, and the cube of the wall superheat.

A kinetic theory treatment of strong condensation in the presence of a non-condensable gas has been developed, extending an intensive condensation treatment for a pure vapor [35JJ]. Despite large variations in number density and pressure of a non-condensable component gas, a kinetic theory analysis suggested that a small amount of non-condensable gas has no influence on the weakly non-linear condensation or evaporation of a vapor [34JJ]. Results reported of film condensation of mixtures of refrigerants 113 and 114 and refrigerants 113 and 11 were well predicted by a solution considering the two independent resistances of the liquid film and the vapor diffusion boundary layer [21JJ]. An approximate method was described for calculation of required heat exchange area for condensation of gas–vapor mixtures, demonstrating satisfactory agreement with experiments [14JJ].

The unsteady flux of condensation nuclei in an expanding supercooled vapor was analytically determined [39JJ]. One-dimensional nozzle flows with non-equilibrium condensation were modeled [10JJ] and extended to supercritical shocks, for which the latent heat addition exceeds the heat input for thermal choking [9JJ].

Options available for improvement of film condensation of pure vapors were reviewed [38JJ]. Heat transfer coefficients by condensation upon a vertical tube were augmented by as much as a factor of 2.8 through the use of non-uniform electric fields produced with helical wire electrodes [44JJ]. Development of a floating OTEC system prompted experimentation with the effects of low frequency, large amplitude periodic motion of a vertical tube upon external filmwise condensation [33JJ]. Heaving (axial motion) had little effect, swaying (lateral motion) produced enhancements increasing with acceleration, and rolling (simulated by pendulum motion) produced enhancements increasing with angular displacement and decreasing with frequency at low frequency, increasing with higher frequency.

Hydrodynamic behavior of the condensing section of a thermosiphon was experimentally observed to be 'highly turbulized' [3JJ]. Experiments with, and modeling of plate-fin devices for fractionating of mixtures were reported [46JJ]. Moisture accumulation and thermal conductivity increase of fibrous insulation material due to moisture migration were analyzed in a transient manner yielding the wet–dry interface location as one of the predicted variables [48JJ]. A stable and convergent numerical method was described, capable of modeling regenerators in which condensation and evaporation occur [49JJ]. Experiments and analysis were presented for simultaneous melting of a vertical planar substrate and condensation upon it in the presence of a non-condensable gas [15JJ]. The reduction of heat transfer due to the non-condensable component was stronger for melting substrates with lower liquid Prandtl number.

CHANGE OF PHASE—FREEZING AND MELTING

The classical Stefan problem, describing the melting or freezing of spheres, cylinders and slabs, continued to receive attention. One paper addressed the multiphase case, with more than one moving boundary separating distinct phases [11JM]. The problem of freezing a saturated liquid inside an infinite circular cylindrical container was solved by fixing the boundary with a logarithmic transformation and obtaining an iterative analytic series solution [21JM]. Approximate analytical methods [19JM] and integral formulations [10JM] were presented for analyzing Stefan problems.

Melting result correlations, based on experiments, were presented for both pure and impure substances [49JM]. A new and efficient algorithm was proposed to be incorporated with the equivalent heat capacity model for the finite element analysis of melting and freezing problems [24JM]. A comparison was made between an approximate analytical solution and a numerical finite difference solution for the one-dimensional solidification of a phase change material of finite size [2JM]. A finite element numerical method based on enthalpy was proposed for the solution of two-dimensional problems dealing with phase change at fixed temperature [4JM]. An algorithm was described that combines a temperature formulation with a finite element treatment of the differential equation and discontinuous integration within two-phase elements to avoid the necessity of regularization [9JM]. Based on the effective heat capacity characteristics of biological materials during freezing, a short-cut equation for predicting their temperature vs time behavior during freezing and thawing has been derived [38JM].

The problem of the flowfield, heat transfer, and melting rate of a solid body immersed in an otherwise quiescent, hot fluid is an interesting example of free convection, differing from the usual free convection problems in that the dominant buoyancy force is due to the fluid–melt density difference rather than the familiar thermal expansion [6JM].

Simple upper and lower limits for the full solidification (melting) time of isothermally heated slabs, cylinders and spheres were derived [5JM]. The method of cubic spline collocation was employed to solve the governing equations of the processes of inward solidification occurring in slabs, cylinders and spheres bounded by a finite wall subject to a convective boundary condition at the outer surface [42JM]. A boundary fixing series technique, previously used on melting and freezing problems where the material was initially at the fusion temperature, was generalized to initially subcooled melting cylinders and spheres [30JM]. Experiments and supplementary numerical solutions have been performed to study the melting of ice [36JM] and other materials [45JM] encapsulated in a horizontal tube. A methodology was set forth for the numerical solution of transient two-dimensional freezing of a material in a vertical tube and results presented for 99% pure n-eicosane, a material for which experimental results are available [47JM, 48JM]. Timewise measurements of in-tube melting in the presence of circumferentially non-uniform heating enabled identification of the pattern of melting for different types of heating and various tube inclinations [46JM]. Melting of ice in porous media has been investigated experimentally and analytically for horizontal and vertical cylindrical capsules [55JM]. The roles of natural and forced convection during solidification of pure tin in an annular crucible were described [54JM].

A theoretical analysis was presented for the phase change process occurring in a cylindrical annulus in which rectangular, uniformly spaced axial fins, spanning the annulus, are attached to the inner isothermal tube, while the outer tube is kept adiabatic [35JM]. A two-dimensional numerical simulation of outward melting of a material contained in a horizontal cylindrical annulus was performed [23JM]. The solidification of a subcooled metallic sphere was analyzed by an enthalpy method [25JM]. Melting heat transfer in an inclined rectangular enclosure was investigated experimentally [57JM]. A study defined the limitations of using a one-dimensional approximation for analyzing buoyancy and surface tension driven natural convection in rectangular cavities during solidification [34JM].

Heat transfer during the melting of ice around a horizontal cylinder was investigated experimentally [58JM] and numerically [22JM]. An approximate three-dimensional solution for melting or freezing around a buried pipe beneath a free surface was presented [61JM]. Melting around a horizontal finned tube was studied [3JM] and a comparison of the phase change about finned and bare tubes was performed [40JM, 41JM].

Results were presented of calculations of the melting rate of a sheet of finite width under the effect of variable power heat flows [52JM]. The two-dimensional steady-state shape of a solidified region, such as a frost layer, was determined analytically for formation on a plate that is convectively cooled [44JM]. The solidification of an infinite liquid slab by linear convection cooling from the adjacent air was considered [20JM]. The phenomenon of melting from a flat plate in a porous medium in the presence of boundary-layer natural convection was analyzed by assuming that the melting takes place at a steady rate [27JM]. The role of natural convection on solid–liquid interface motion and heat transfer was described for melting and solidification of a pure metal on a vertical wall [16JM, 57JM]. The melting process of ice–air composite materials was investigated for the case where heat was supplied from the bottom and lost from the top of the body [1JM]. Experiments were performed to gain an understanding of the convection process occurring in a warm liquid pool as it penetrates into an underlying meltable solid of less dense material [15JM]. The linear convection instabilities of a fluid layer of binary alloy, cooled from above and consequently frozen at the bottom, were described [26JM].

An analysis of one-sided freezing of moist soil included the allowance for the phase transition of moisture in a certain temperature range and moisture migration in the thawed and freezing zones [60JM].

A dependence was proposed for determining the heat transfer coefficient at the boundary of an ice mass and a water film running down the ice in the presence of thawing [17JM]. An experimental investigation of snow melting by showering the snow layer with a calcium chloride aqueous solution clarifies the influences of initial concentration of the solution, amount of showering solution and density of snow sample on the melting rate [29JM]. A paper described the melting of a horizontal ice layer from above by an aqua-solvent with a low solidification point (calcium chloride and urea solutes) [51JM].

The melting of a semi-transparent material by radiation was studied experimentally and analytically [12JM]. A numerical analysis was performed of thermocapillary flow in a rectangular cavity during laser melting [50JM]. In a study of the temperature fields associated with laser melting and subsequent recrystallization of a thin silicon film on a glass substrate, particular attention was paid to the change in the material properties with temperature and to the change in reflectivity which occurs when the silicon changes phase [18JM]. Companion papers described exact solutions to problems associated with laser melting of solids, one for time intervals less or equal to the transit time [13JM] and the other for larger time intervals [14JM].

Studies of close-contact melting [32JM, 33JM], contact melting [39JM], and contact ablative melting [31JM] were performed.

The solidification process during the continuous casting of an ingot by withdrawal from a mold was analyzed assuming a constant convective heat transfer coefficient at the outside surface of the ingot [43JM]. The continuous casting problem was also analyzed via the variational inequalities approach [37JM]. Three papers describe gas melting. A three-dimensional numerical method was presented to simulate the effect of electric boosting on glass melt circulation and heat transfer in a glass melting furnace [53JM]. Mathematical models were constructed to predict the temperature distribution and heat transfer in a glass batch blanket and to simulate the effects of individual factors on the conversion process [59JM] and to calculate Joule heat release, glass flow and heat transfer in electric glass furnaces [8JM].

A theoretical study was conducted to investigate the effect of freezing on the heat transfer characteristics for the turbulent flow of a heat generating fluid in a cooled circular tube [28JM]. The critical condition for solidification blockage of laminar straight pipe flow in an arbitrary piping system was derived by comparing two pressure differences in the cooling section, one of which depends on the system (driving pressure difference), and the other is given by a numerical calculation of steady laminar pipe flow with internal fluid solidification [7JM].

RADIATION IN PARTICIPATING MEDIA AND SURFACE RADIATION

Radiation in participating media

Reference [94K] presents and compares two techniques for evaluating the emission integrals used for discrete ordinates solution. Vector algorithms for Chandrasekhar H-functions for inhomogeneous media are reported [55K]. By combining a weighted set of distributed internal sources, the photon path length analysis is extended to planar layers with arbitrary temperature distributions [102K]. A generalized spherical harmonics solution for radiative transfer models, including polarization effects, emphasizes the numerical aspects for accuracy [45K]. The spherical harmonics approximation solution to the equation of transfer in plane-parallel, homogeneous, anisotropic scattering (Rayleigh and Henyey–Greenstein) media are obtained by a Chebyshev collocation method [62K]. For isotropic scattering media of the same geometry, ref. [112K] reports on a new, efficient method of analysis, which uses the natural eigenfunctions of the problem. Four-flux model solutions of special types of Lorenz–Mie scatter centers embedded in a slab are presented [76K]. A generalized Eddington approximation for the slab geometry is presented [124K]. Matrix formulations are presented for planar scattering media using the discrete-ordinates and the matrix-operator methods [83K]. A modified Monte Carlo method is reported [64K], which reduces the computing time and improves the convergence stability.

A modified F_N method is used to study the radiative transport in a planar medium with azimuthally unsymmetrical incidence [67K]. A zonal method is proposed [2K], which takes into account the anisotropic character of volumetric and surface scattering. Solution of the radiative transfer in a two-phase medium for a Markov process is reported [120K]. The Sobolev probabilistic method [121K] is used to obtain an exact solution of the equation of transfer in a gas containing particles of its condensed phase. A linearized differential approximation is invoked to consider the transient flow of optically thick, dusty gas in a vertical channel [12K]. Benchmark solutions are presented, four or five digit accuracy, for the time-dependent reflected photon intensity from an anisotropic scattering semi-infinite medium [44K].

Spherical harmonics approximation is used to model radiative transfer in a finite length cylindrical vessel, containing high temperature aerosols that absorb, emit and scatter [77K]. The integral form of the solution of the equation of transfer is shown to reduce the number of independent variables from three to one for isotropically scattering, inhomogeneous solid cylinders [111K]. Reference [80K] considers numerical solutions for axisymmetric, finite cylindrical enclosures containing radiatively participating gases and particles. A solution method for solving the equation of transfer in an isotropically scattering, inhomogeneous solid sphere is also presented [113K]. The far field solution and the energy flux from a moving source in an anisotropic medium is presented [68K]. A rigorous formulation of the problem of radiative transfer in an anisotropic, fibrous medium shows a strong dependence of the transport properties on the different orientations of fibers [71K].

Theoretical and experimental results of backscattering from an optically thick, scattering medium exposed to a laser beam are presented [87K]. A method based on the principles of invariant imbedding, is presented for solutions in two-dimensional anisotropically scattering medium exposed to arbitrary boundary conditions [106K]. A three-dimensional code, based on the diffusion approximation, is used to model the spatial distribution of radiant energy from volumetric isotropic sources [127K].

A hybrid Galerkin-iterative scheme is used to provide a short time solution for coupled conduction and radiation in a participating slab [107K]. Radiation scaling laws are applied to model combined mode heat transfer in planar geometry [70K]. The transient temperature distribution of an absorbing, emitting multilayer composite wall, suddenly exposed to radiative flux, is influenced by both radiation and conduction in each layer [116K]. Effects of the non-linear heat generation, and combined conduction and radiation treated at the optically thick limit, on the vibrational heating of semitransparent polymers are considered [50K]. The effect of scattering in one layer, when the non-stationary radiation–conduction problem in a system of two layers is considered, is presented [97K].

The combined natural convection and radiation heat transfer from pin-fin arrays in air is measured, and the contribution from the radiation is determined analytically to be in the 25–40% range [104K]. The Milne–Eddington approximation is used to express the two-dimensional radiative transfer inside a horizontal cylindrical annulus filled with absorbing, emitting non-gray Boussinesq fluid [88K]. A numerical study of non-gray gases in a flow system, compares the results with those obtained by using a gray gas assumption [54K]. The effect of radiation on the heat transfer in the boundary layer flow along a flat plate are described as a prescribed function of distance from the slit, where the constant velocity flow is introduced into a fluid at rest [21K]. The presence of both the radiation and the magnetic fields is found to resist the formation of shock in electrically conducting and thermally radiating gases, which are treated as optically thin [100K]. An asymptotic representation of a point-source thermal explosion, dominated by radiative heat transfer, makes it possible to analyze the generation of an isothermal shock wave [95K]. Radiative energy transfer and equilibrium chemical reactions in the compressed shock layer around three-dimensional and axisymmetric bodies are considered [5K].

The Surinov generalized zonal method is applied to solve for the radiative transfer in a conical chamber with absorbing and anisotropically scattering medium [48K]. Locally variable radiative heat transfer between long cylinders that contain emitting and absorbing gases is calculated [60K]. A loss of visibility study considers laser reflection from a scattering medium with a reflecting substrate [74K]. Least squares smoothing of direct-exchange areas in zonal analysis, using Lagrange multipliers, is presented [69K]. A local entropy production expression includes the effect of radiation, expressed in terms of radiative stress [6K]. A study of the characteristics of fine-particle semi-transparent suspensions considers the optical depth and boundary condition effects [59K]. Liquid-droplet radiators for spacecraft thermal control are shown to be 3–5 times lighter than conventional radiators [110K]. Calculations of emitted radiation from boron slurry-fueled jet engine exhaust considers the effect of B_2O_3 particles [86K].

Radiation in combustion systems

A two-dimensional model is considered when the heat ray method is applied to radiative transfer problems in furnaces [53K]. The total effective absorptivity and emissivity of fluidized bed combustors are studied, and the important dimensionless parameters that are needed in the radiative transfer correlations are pointed out [16K]. An axisymmetric cylindrical enclosure, containing inhomogeneous and non-isothermal gases and particles, is studied to model a typical gas-turbine combustor [79K]. Direct exchange areas for the zone method are provided to evaluate the radiative transfer in rectangular, gas-filled furnaces [118K]. An algorithm for solving the conjugate problem, which arises in furnaces with a protective atmosphere, is presented [73K]. The effect of isotropic and anisotropic scattering, on the heat transfer in semi-infinite furnace slabs, are studied by using the zone and the Monte Carlo methods [39K]. The enhancement due to the addition of a solid surface, between parallel plates containing non-gray combustion gases, is shown to be as high as 30% [54K]. The influence of the wall emissivity on the performance of high temperature, radiation dominated furnaces is considered [35K]. A review of the models useful for calculating radiative transfer in furnaces is presented [123K].

The influence, of the burner geometry and the fluid parameters, on the local and the mean emissivity of gas diffusion flames, is studied [115K]. Radiation from a methane–air flame which is electrically augmented to enhance the flame temperature is examined [61K]. Reference [31K] presents analytical solutions for the structure and the burning speeds in rich mixtures of combustible solid particles and gaseous oxidizer, viewed as absorbing–emitting media. Light transmission and emission measurements, of the deflagation of ammonium perchlorate with carbon black and copper chromite catalyst additives, is used to quantify the amount of particle radiative feedback [17K]. The dynamic light scattering technique is used to measure the soot particle size distributions, number density, and the total volume, in premixed methane–oxygen flames [99K]. Reference [40K] establishes a framework for computing the scattering characteristics of agglomerated soot spheres, and considers the effects of radial inhomogeneity and agglomeration on light scattering measurements in flames. Emission measurements of high temperature water vapor, produced as exhaust gas from burning natural gas and oxygen, are compared with predicted values [27K].

Surface radiation

A numerical method for calculating the configuration factor, based on the unit-sphere method, uses the computer graphics technique of ray casting. The method is shown to give accurate results for complex geometries and does not suffer from statistical errors associated with the Monte Carlo methods [78K]. Reference [105K] discusses the reliability of the Monte Carlo method for calculating the view factors. A plating algorithm, where the emissivities of surfaces in an enclosure are made to vary from one to its actual value, is used to obtain the script-F transfer factors [37K]. The concept of multiple Markov chains is applied to develop a stochastic approach for radiative exchange in enclosures with directional–bidirectional properties [84K]. Radiative heat transfer across and down a long cylindrical capillary pore is presented [117K]. A study compares simple, surface radiation exchange models that can be used to simulate the thermal behavior of buildings [3K]. Conductive and radiative heat transfer in circular and longitudinal finned tube systems are measured experimentally and compared with numerical predictions [108K]. An approximate computation scheme is proposed to predict the heating of massive, optically dense bodies in a radiation dominated furnace [32K]. An asymptotic, large time solution for the convection Stefan problem with surface radiation is presented [114K]. A model for the interaction between intense radiation and a liquid, takes the absorption coefficient of the liquid into account [46K]. Heat transfer from a source in a transparent cavity with a conducting shell is considered [91K]. A radiative transfer model for severe fuel damage analysis accounts for anisotropic effects of reflected radiation, with simplified view factor calculations [103K].

Radiative properties

A method, for determining the optical properties of semitransparent materials at high temperatures from two independent measurements, is used to obtain the properties of fused quartz and sapphire at 1000°C and 0.6–13 μm [82K]. Reference [30K] describes an experimental rig which measures the directional–hemispherical transmittance and reflectance of porous materials in the 9–11 μm range. Optical constants of strongly absorbing media are obtained from considering the minimum, parallel polarized reflectance measurements [75K]. Two new techniques for determining the thermal radiative properties of thin fabrics are reported [19K]. A technique, developed for evaluating surface coating effectiveness, leads to an analysis of the characteristics of a simple energy absorption transducer [11K]. The method of moments is used to model conduction and radiation in a translucent scattering medium, and the predicted temperatures are compared with the experimental measurements to obtain the radiative properties [92K]. Analytical error estimates for the time-dependent radiative-transfer inverse problem, used to infer the albedo and the Legendre moments of the phase function, are presented [36K].

Radiative characteristics for fly ash and coal are obtained numerically by modeling them as clouds of spherical particles illuminated by blackbody radiation [14K]. The only reported results of the optical constants of propellent-grade ammonium perchlorate are obtained by a combination of dispersion equation curve-fitting and normal spectral reflectance measurements [89K]. Simple expressions for the temperature dependence of the index of refraction of sapphire are given [109K]. Calculations of the mean hemispherical emissivity of hot glass in various configurations are presented [57K]. Reflective characteristics are used to study the radiation properties of industrial refractories of zirconium dioxide [126K]. A stratified media theory is applied to the results of an experimental study of the emissivities of oxide films on metal surfaces [4K]. Infra-red radiative heat transfer in highly transparent silica aerogel is obtained by measuring the extinction [20K].

A theoretical investigation of the dependent scattering properties are presented, assuming the Rayleigh–Debye scattering approximation, and the scattering efficiencies are shown to be smaller than the independent efficiencies [22K]. An experimental investigation of the dependent scattering compares the measured bidirectional transmittance and reflectance to the theoretical predictions [125K]. Computer calculations, which apply the theory of diffraction, show a range of concentrations where the radiative properties of the dispersion is dependent on the distance between the particles [98K]. A localized approximation to the generalized Lorenz–Mie theory is introduced and compared with the Rayleigh–Gans theory [49K]. A simple numerical scheme, based on the Fraunhofer approximation, is used to calculate the forward scattering by a sphere located anywhere in a Guassian beam [24K]. An experimental study designed to distinguish between the transmitted and the forward scattered intensities, compares the measured results with calculations [10K]. The asymptotic form of the Mie-scattering amplitude, useful for large size parameter calculations, is presented [7K]. Kramers–Kronig relations, which can be written independent of any material constants, are used to infer refractive indices from spectral extinction data, without any knowledge of the index of refraction at any frequency [66K]. Correction charts for particle size distribution measurements, needed due to the multiple scattering effects, are presented [47K].

A perturbative approach to scattering by a single-layered sphere is applied to the case of absorption of light by water droplets contaminated with soot [13K]. Using a full wave approach, the particle surface roughness is shown to have a significant effect on the diffuse specific intensities [9K]. Scattering and depolarization by conducting cylinders with rough surfaces are also considered [8K]. The multiple Laplace transform is applied to study the electromagnetic reflection from arbitrary smooth convex cylinders [56K]. A technique is given for computing the scattering by targets which can be subdivided into circular disks [51K]. The iterative extended boundary condition method is utilized to calculate the scattering and the absorption of aerosols that are modeled by spheroids of high aspect ratio [58K]. A study of the scattering from non-spherical particles, which have radii described as functions of Chebyshev polynomials, shows that concavity enhances the spherical–nonspherical differences [81K]. Irregularities, on the surfaces of particles that are large compared with the incident wavelength, are modeled by a function of fractal type [15K].

The penetration of pulse of laser radiation through the atmosphere is shown to allow for the cooling of the water vapor in the channel around the beam, when the pulse duration is controlled [72K]. A wide-band absorption coefficient integration kernel is introduced, which transforms the wave number integration to a more convenient integration over the absorption coefficient [38K]. The infra-red absorption properties of carbon dioxide are the topic of a number of studies [1K, 28K, 29K, 33K, 41K, 93K, 96K]. Absorption properties of carbon monoxide [43K, 90K], water vapor [33K], and gaseous methane [25K, 26K, 42K] are also considered.

Experimental systems

A unique apparatus is developed, which can be used to measure the emittance of semitransparent, porous and particulate media [119K]. Correction factors, which are necessary for integrating spheres with one port, when the sample is used in place of an open port, is calculated with a finite difference method [63K]. Infra-red lasers in the 11–13 or 14 μm wavelengths operate by pumping NH_3 [65K, 101K]. Characteristics of silicon avalanche photodiodes are examined to assess their suitability for photon correlation measurements [18K]. An optimized geometry of far-IR photoconductive detectors is presented [122K]. A cryogenic charge amplifier system is developed for an InSb photodiode array for use in high-resolution infra-red spectrometers [52K]. Darkening of silver halide optical fibers, transparent in the middle infra-red and useful for transmitting a CO_2 laser wavelength of 10.6 μm, is considered [23K]. Mid-infra-red reflectance spectra of sulfur, gold, KBr, halon, and recommendations to their usefulness as reflectance standards are presented [85K].

NUMERICAL METHODS

Numerical methods are described and used in many papers. In this review, the papers that focus on the application of a numerical method are included in the appropriate application category. The papers that emphasize the details of the numerical method are reviewed in this section.

Among topics of general interest, ref. [76N] surveys the application of parallel and vector computations in heat transfer and fluid flow. The use of various spreadsheet programs for solving heat transfer problems on microcomputers is described in ref. [19N]. Various strategies for solving linear and non-linear simultaneous equations have been described in refs. [13N, 41N, 65N]. Reference [49N] deals with a technique for grid generation.

In the area of heat conduction, a number of methods have been developed for non-linear inverse heat conduction [32N, 33N, 72N, 81N]. Finite element analysis has been applied to non-linear heat conduction problems [74N]. Reference [34N] proposes a unified model for axisymmetric heat conduction. Integral transform techniques have been combined with the finite element method for heat conduction [15N]. New types of finite elements have been proposed for heat conduction [78N, 79N]. Applications of boundary element methods to heat conduction are presented in refs. [1N, 55N, 58N]. Various novel techniques for transient heat conduction problems have been presented in refs. [8N, 12N, 21N, 47N, 77N].

Problems involving phase change have been analyzed numerically. Reference [3N] pertains to the growth of crystals from the melt, while numerical techniques for the Stefan problem are developed in refs. [91N, 93N]. The concept of lumped capacitance has been used in finite element methods for phase change [67N].

The question of numerical accuracy for the combined convection–diffusion problem continues to be a topic of intensive research. Reference [66N] evaluates eight different schemes for the problem. The influence of upstream approximations in curved grids is discussed in ref. [27N]. Tetrahedral elements for convection–diffusion problems are employed in ref. [54N]. A new skew, upwind procedure is presented in ref. [75N]. Weighted finite difference methods are proposed in refs. [17N, 64N]. A new finite element formulation for fluid flow and convection–diffusion problems is developed in refs. [35N–39N]. Additional studies of the advection equation are contained in refs. [5N, 20N, 40N, 59N, 62N, 80N].

Adaptive grid methods have been investigated [51N, 61N]. Multi-grid procedures for the solution of recirculating fluid flow have been developed [52N, 86N–88N] and shown to be significantly more efficient than other available methods. The multi-grid technique is also used for the solution of the Euler equation [45N]. Techniques used for the solution of the Euler or Navier–Stokes equations are compared in refs. [2N, 16N, 89N]. Other studies related to the Euler equation have been reported in refs. [12N, 44N, 63N, 94N]. Reference [70N] presents an implementation of the Osher upward scheme.

A large number of new methods have been proposed for the solution of compressible and incompressible fluid flows. Methods that employ the boundary layer characteristics of the flow are presented in refs. [22N, 31N, 56N, 92N]. The vorticity-based methods are described in refs. [25N, 95N]. Calculations have been presented for compressible flow in refs. [4N, 90N]. Among the new methods proposed for fluid flow refs. [42N, 43N] use operator splitting. The use of general orthogonal coordinates is described in ref. [71N]. The problem of temperature–velocity coupling is addressed in ref. [28N], while an equal-order interpolation method is worked out in ref. [69N]. A number of other techniques for solving the flow equation have been described in refs. [6N, 29N, 30N, 57N, 68N, 73N, 83N, 84N].

Comparisons of a class of numerical techniques for certain test problems are presented in refs. [11N, 46N, 60N]. Various special aspects of numerical methods such as grid skewness, nonlinearity, convergence rate, and mesh refinement are discussed in refs. [7N, 10N, 23N, 26N, 53N]. Different schemes have been compared for solving the flow past a sphere [14N] and around a cylinder [9N]. Analysis of problems with free surfaces has been described in refs. [18N, 50N].

TRANSPORT—PROPERTIES

Thermodynamic

A number of papers address the determination of thermodynamic properties. Acoustic gas analyzers for determining binary-gas composition are described [58P, 76P] and a thermodynamic method for measuring local steam quality given [26P]. An image processing system and diamond-anvil cells are used to obtain pressure–volume measurements [74P], gas expansion to determine volumes [33P], and a densitometer for gaining absolute measures of temperature dependence of density, partial volumes, and thermal expansivity of solids and liquids [17P]. Also reported is an improved method for precisely determining the compressibility factor from measurements of refractive index [11P].

Phase transition effects are considered: first the melting lines of simple substances, their thermodynamic similarity and behavior of thermal properties [69P] and second, the relation between thermophysical properties of new ceramic materials and this phenomenon [86P]. Other techniques for measuring properties include a new procedure for obtaining the heat of solid deformation [49P], a new instrument for acoustically measuring complex adiabatic compressibility in liquids [73P] and a simple procedure for determining the Seebeck coefficient of thermoelectric materials [32P].

For specific substances there is a new equation of state for aluminum [40P], measured high pressure densities for argon–helium and argon–neon mixtures [83P], and a transformed psychrometric chart for use in drying technology [70P]. A dual-slope method is presented for measuring specific heats [62P]; other specific heat data are presented for n-pentane, n-hexane and n-heptane at high pressure [20P]. Ni_3Al at low temperature [39P], and some stainless steels and Fe–Ni alloys [16P]. For black phosphorus thermal and elastic properties are reported [89P].

Transport

Interest in special systems and ordinary ones at extremes of temperature continues. A model and calculations of transport coefficients for polyatomic gases are given [81P, 82P] as well as a discussion of the structure of liquids and their thermal properties [21P]. For two-phase materials, a model is presented for estimating transport quantities [1P]. Another study [30P] shows how thermal properties may be estimated by a non-linear least squares method. For electrically conducting materials thermal transport is studied using the transient hot-strip technique [34P]. For chemical-equilibrium flows of partially dissociated and ionized gas mixtures, the effective transport coefficients are defined and computed [80P]. Transport properties of high purity, polycrystalline titanium diboride are reported [85P] and in the area of drying technology some physico-thermal properties of rice bran will be of interest [24P].

Diffusion rates in solids due to shock compression are reported [46P] as is the development of a new fast response probe for studying diffusion in atmospheric air [10P].

Thermal diffusivity measurements are described at low temperature using the laser-flash method [48P], for solids by the two-beam photoacoustic phase measurement [54P], and the quantity defined for shifting composition systems [23P]. The increasing occurrence of special systems undergoing heat transfer leads to the study of equivalent thermal diffusivities of non-homogeneous materials by numerical means [9P], the report of thermal diffusivity in plasma sprayed multi-coatings (apparent) [31P], powders and porous media [61P], ceramics [65P], and uni-directional fiber-reinforced composites [75P].

A number of experiments for measuring thermal conductivity are presented. For systems under hydrostatic pressure techniques are given for determining thermal conductivity (and heat capacity) [3P]; also under pressure, a d.c.–a.c. hot-wire procedure for determining thermal conductivity (and other thermophysical properties) is described [52P]. A transient technique for measuring thermal conductivity is first theoretically developed [56P] and the apparatus described [57P]. For non-homogeneous samples the apparent thermal conductance is measured [51P]. Using a model of a semi-infinite body with a pulsed annular heat source, thermophysical characteristics of materials may be determined without loss of their integrity [66P, 67P].

Improvement in accuracy is the objective of two studies: an experimental and theoretical investigation of the influence of radiative heat transfer on the effective thermal conductivity of liquids [29P] and a proposal, with special respect to connection and radiative effects, for thermal conductivity standards to be used in establishing liquid thermal conductivities [28P]. The instability of thermal conductivity values due to stratification is considered as well [87P]. When using the transient line-source technique it is demonstrated that the end-effect error can be kept so small as not to require correction [47P]. For guarded hot-plates thermal imbalance errors and effective area are discussed [55P]. The general solution for non-linear steady-state heat conduction in a metal conducting electrical current is solved for any temperature variation in thermal and electrical conductivities, allowing interesting comparisons to be made between the variable and constant conductivity cases [90P].

The variety of systems for which thermal conductivity data is required is apparent in the number of papers having this purpose: the measurement of effective thermal conductivity of porous spheres at high temperature [5P], thermal properties of moist porous media below 0°C [78P], and measured thermal conductivity of packed metal powders at different densities and an associated theoretical model [35P, 53P]. The effect of temperature on viscoplastic pore collapse is also described [14P]. In a related vein effective thermal conductivities of loose granular materials are proposed [64P], a heat pulse, line-source method for determining thermal conductivity of consolidated rocks is reported [27P], and the effect of moisture on the thermal conductivity of lightweight aggregate concrete described [71P].

Composite and multilayer systems also attract keen interest as evident by a monograph for calculating the transverse thermal conductivity of uniaxial composite lamina [43P], coated filler composites thermal conductivity [37P], effective thermal conductivity of a composite material with spherical inclusions [22P], and for fiber-reinforced materials [77P].

In the agricultural area experimental thermal conductivities are reported for grains using a line-source method [41P] and for haylage at various bulk densities and moisture content [45P]. The thermal conductivity of tin between 15 and 500°C is given [38P]. Also at temperatures above atmospheric thermal conductivity values are reported for evacuated, transparent silica aerogel tiles [13P], spinel ferrite (400–1000 K) [25P], and plasma sprayed stabilized zirconia and nickel-based coatings [12P]. Factors having an effect on the mean effective thermal conductivity of a melt of glass–plastics are reported [42P].

In the lower temperature regime thermal conductivity results are given for ethane (110–325 K) [63P], pure ice and hydrates [4P], and the effect of plastic deformation on bismuth alloys between 1.5 and 300 K presented [72P]. A simple model of the thermal impedance present in the heat transfer between dielectric solid and superconducting metal with deformation caused defects is found consistent with new and published data [88P].

In the optical area, thermal conductivities of optical coatings are reported [59P]; in the space-vehicle propulsion area thermophysical properties of propellents are given [68P].

Thermal insulations attract the attention of a number of investigators. The nonsteady-state behavior of such materials is discussed [50P], the local thermal conductivity in inhomogeneous glass fiber insulations analyzed [60P] and the temperature variation of the thermal conductivity of self-pumping multilayer insulation reported [36P]. For spray-applied insulations the moisture gain and influence on effective thermal conductivity assessed [6P]. The efficacy of rigid polyurethane foam is analyzed by examining the heat transfer mechanisms through the foam components (gas voids and solid sections) with the prospect of optimizing the system for maximum insulating efficiency [18P]. The influence of lining properties on the control characteristics of industrial furnaces is modeled to obtain wall temperature oscillations [44P].

Where surface tension is a consideration, a cubic equation for its prediction is described [8P].

For contributions to the knowledge of viscosity there are reports on argon at high densities [79P] and the density influence on benzene and methane [84P]. A description of a capillary viscometer for evaluating low-viscosity solutions at elevated temperatures [19P], one for low frequency, low shear rate measurements [7P], and a dual chamber capillary viscometer to study concentrated polymer solutions at elevated temperatures [2P] comprise the experimental techniques report.

HEAT TRANSFER APPLICATION—HEAT PIPES AND HEAT EXCHANGERS

Interest continues to be shown in various schemes for improving heat exchange under a variety of special applications.

For packed beds a two-part study [101Q, 102Q] examines particle to particle heat exchange first by predicting performance characteristics through modeling and simulations and then by examining the design characteristics and performance of a prototype. Other papers report the results of laboratory-scale tests on gas–solid fluidized bed behavior and the influence on bed properties [1Q]; the heat transfer characteristics of a low-pressure-loss fluidized-bed exchanger with single row tubes [4Q]; and a model for enhanced cooling near the edge of a packed bed [17Q]. A review of heat recovery systems from solid particles or gas with very high temperatures [74Q] should be useful. Related work concerns the liquid content and heat transfer in trickle-bed reactors during intensive gas–liquid interaction [68Q] and the development of a high efficiency packed bed heat exchanger for residential application [93Q].

Devices concerned with condensation heat transfer includes horizontal plain and low-finned condenser tubes, examined for the effect of fin spacing and drainage strips on heat transfer and condensate retention [113Q]; a model of heat and mass exchange on a rectification plate with cold reflux [51Q]; and heat recovery from a spray dryer using a glass tube exchanger [19Q].

The role of contact resistance is taken up by a study of the influence of interface thermal contact resistance on the heat transfer performance of prestressed duplex tubes [8Q]. A related paper examines the thermal constriction resistance at the interface of double tubes used increasingly in solar energy applications [109Q]. The importance of crevices formed between tubes and tube plate on heat exchanger operation is considered [2Q].

A general article describes the features of direct contact heat exchangers noting their increased performance, decreased first cost and increased range of application [13Q]. For liquid–liquid direct-contact heat exchangers the temperature jump is considered [41Q].

The augmentation of heat transfer through the use of extended surfaces is explored in a number of papers. The general efficacy of finned tubes in heat exchangers is considered and shown to nearly double the heat transfer accomplished with plain tubes [71Q]. For convective pins with uniform internal heat generation optimal dimensions are sought [85Q]. In a vertical-tube heat and mass exchanger involving an external water film and internal air flow spaced transverse wires are used to promote the process [110Q]. For the case of the bayonet tube heat exchanger the influence of radiation heat transfer is analyzed [58Q] and for a finned wall located in cross-flowing air in a rectangular duct the heat transfer and pressure drop are studied experimentally [64Q]. For industrial finned tubes performance characteristics are given using dimensional parameters [54Q].

The fouling of heat exchangers during use evades solution since relatively little is known about the underlying mechanisms. The precipitation and particulate fouling on the heat transfer surface is considered [53Q]; the scaling of plain and externally finned heat exchanger tubes reported [99Q]; and the results of new investigations of surface fouling by sedimentation and crystallization described [52Q]. The control of heat exchangers with tube-side chemical reaction fouling is simulated [24Q]. To combat fouling ref. [47Q] describes the fluid bed heat exchanger developed in the Netherlands which depends on fluidized particles in the exchanger tubes to break up boundary layers. Specific applications include the effect of ash deposits on heat transfer coefficients in convective boiler tube banks [81Q] and other heat exchangers [63Q]. To study depositions occurring during the processing of milk experiments were conducted on a platinum wire to gauge the effect of acidity and preholding [5Q].

Plate type heat exchangers receive consideration from a number of investigators. Flow distribution, pressure drop and heat transfer are studied experimentally and theoretically [10Q]; also an array of plates aligned at angles to the flow in a duct [56Q]. The flow mechanisms involved in the performance of interrupted-plate exchangers is studied [70Q] and a calculation method for evaporators with vertical channels [30Q]. In a two-part study the fluid flow [112Q] and heat transfer [55Q] in a plate-fin and square-tube exchanger is analyzed. Matrix heat exchangers are studied in ref. [7Q] where a procedure is proposed for calculating the performance characteristics of an exchanger made of perforated plates and in ref. [16Q] where the performance of laminar flow heat transfer in fine matrices is assessed theoretically and confirmed experimentally. A mathematical model of heat and mass transfer on the rotating evaporator surface in a centrifugal molecular still is developed [37Q] and the results given for a wall-type, air-to-air, counter flow exchanger used in ventilation practice [108Q]. Two studies deal with the design aspects of plate heat exchangers, one describing exchanger dimensions and performance in terms of basic dimensionless groups [22Q], the other outlining a procedure for obtaining simple models from the generalized flow diagrams of the exchanger [84Q].

Tube heat exchangers are joined by a new design which is said to minimize the two most serious equipment problems: surface fouling and gasket leakage through a redesign of the transfer surface geometry and fluid flow pattern [62Q]. Other papers describe a variety of approaches to improve exchanger performance: the use of dented tubes [89Q]; the vortex flow in twisted tubes [18Q]; effect of interbaffle spacing on heat transfer and pressure drop [103Q]; and the effectiveness of series assemblies of divided-flow heat exchangers [77Q]. Thermal expansion of a duplex exchanger tube alters the gap-dependent contact resistance at the interface giving rise to more than one steady-state solution [9Q]. Further special considerations include: exact transient solutions of parallel-current transfer processing [57Q]; the dynamic analysis of a multi-concentric cylindrical heat exchanger [105Q]; the determination of transfer coefficients in a short-tube economizer operating in the transition region [75Q]; and a transient exchanger evaluation test for arbitrary fluid inlet temperature variation and longitudinal core conductance [69Q].

Crossflow heat exchange studies include heat transfer in tube bundles at low Reynolds numbers [36Q], the dynamic behavior of such heat exchangers [23Q], and an analysis of crossflow heat exchangers [107Q]. Related to these studies is one examining two-pass counter crossflow heat exchangers with both fluids unmixed throughout [28Q].

An experimental study [66Q] reports shell-side local heat transfer coefficients in single phase flow.

The following papers are distinguished by the special circumstances attending the investigation: feasibility and performance curves for intermittent earth tube heat exchangers [82Q]; the design of multi-tubular reactors with heat carrier flowing parallel to tubes [104Q]; heat exchange in oil boilers [98Q], and pressure drop and heat transfer in gas-cooled rod bundles [34Q]. In a similar vein, there are reports on heat transfer from parallel-horizontal cylinder rows under corona discharge [49Q]; the theoretical calculation of the thermal efficiency of an evacuated tubular collector [94Q], and an assessment of the air-side performance of air-cooled heat exchangers [12Q].

For design purposes there are some general discussions [25Q, 26Q] as well as specific topics: computer controlled dimensioning of bundled-tube heat exchangers [91Q], direct calculation of exchanger exit temperatures in concurrent flow [83Q]; the design of an apparatus for heat exchange using saturated and underheated superfluid helium (He II) [11Q] and design criteria for nuclear heat exchangers in advanced high temperature reactors [73Q]. Shell-and-tube exchangers having improved design features [87Q] and charts for estimating the performance and design of heat exchangers [106Q] concludes the design aspects.

Unusual application of heat transfer occurs during the use of an inverse finite element to analyze stationary arc welding processes [33Q], a report on platinum black powder as a heat exchanger material at low temperatures [88Q], and the design of aeroassisted orbital transfer vehicle heat shields for a drag brake [79Q].

Heat pipes are a major area of activity. A review paper [97Q] presents the basic concepts, recent innovations in design and applications; others discuss temperature drops in heat pipes [92Q] and the effect of different configurations on performance of heat pipe recovery systems [6Q]. Fluid mechanics effects concern a number of investigators: analysis of vapor flow in a double-walled concentric heat pipe [20Q], the onset of flows and stabilities in parallel loop devices [117Q], flow pattern observations in a circular open thermosyphon [111Q], vapor flow features in slender, cylindrical units (numerical) [72Q], and the initiation of fluid motion in a toroidal heat pipe [116Q]. In space application, the formation of excess liquid in orbital tests of axially grooved heat pipes is reported [67Q].

For closed thermosyphons, the effects of pressure and inclination over a wide range are noted [27Q]; another work [78Q] stresses the effect of inclination on the limiting heat flux, and a third [3Q] considers the heat transfer efficacy of heat pipes with continuous corrugated wicks. For low temperature devices ref. [50Q] considers the influence of heat flow characteristics upon the vapor flow and ref. [49Q] reports on experiments revealing the operating regimes under nearly isothermal conditions. The calculation of heat pipe parameters at high temperature is considered [59Q] and an outdoor method for testing an evacuated tubular collector with heat pipe for solar application described [44Q]. Also for solar conditions, an analysis of a heat pipe absorber array is given [35Q].

Further specific applications consider a heat pipe economy cycle [95Q], a gravity assisted device used with concrete shell steam condensers [45Q] performance of gravity-assisted potassium units [80Q], and the maximum heat flow for a system using a sulfur–iodine mixture (600–900 K) [100Q].

Regenerators receive the attention of a number of workers. A procedure of selecting the optimum matrix for stacked wire gauges is described [29Q] and the thermal performance of diabatic cyclic devices analyzed [31Q]. To improve the cold-side heat transfer coefficient consideration is given to injecting steam because of its radiation properties [39Q]. Two-dimensional heat transfer analysis is used to study high temperature exchange in a closed power cycle MHD regenerator [114Q]. For a regenerator of finite mass the performance of a Stirling engine is reported [42Q].

The thermodynamics of heat exchangers enters from a number of viewpoints. Such considerations appear in the design of long-life, high temperature devices [115Q], in assessing losses due to exchanger irreversibility [43Q] and the entropy generation in such processes [96Q]. Natural circulating water systems are subject to thermodynamic analysis [40Q].

Using load curves, heat exchanger networks are optimized from a second law viewpoint [15Q]. In a two part study of performance of a scraped-surface heat exchanger the principal models for heat transfer and power consumption are reviewed [60Q] and the effect of the axial diffusion of heat [61Q]. Thermal energy recovery systems generally are subjected to thermodynamic optimization [38Q]. Further work on heat exchanger networks include a combined energy-economics approach [32Q], the synthesis of flexible nets for multiperiod operation [21Q], and the influence of pinch phenomena in providing improved network synthesis [86Q].

Several aspects of vapor generators and evaporators receive study. Correlations for rifled tubing in variable pressure boilers are given [65Q], the heat transfer in critical and supercritical zones of sodium–water vapor generators reported [46Q], and a boiler described [14Q] which uses radiator elements for steam generation from solid fuel. For the stationary heating-plane of indirectly heated dryers heat transfer coefficients are provided [76Q] and a monograph devised for predicting the hydrostatic head effect in process plant evaporators [90Q].

HEAT TRANSFER APPLICATIONS—GENERAL

Several papers dealt with heat transfer in electronic and electrical devices. Empirically derived natural convection correlations extracted from the scientific literature were compared with non-dimensionalized data obtained from physical models of uniformly heated electronic circuit cards vertically mounted in a frame [25S]. A thermal model for a hybrid IC in which the conductive heat transfer takes place from one or two large surfaces of the substrate in any combination with the ends was presented [2S]. A simulation model was used to predict the temperature rise for multichip electronic packages [24S]. Methods of effectively cooling computers and high performance electronic modules were presented along with several examples [49S]. The finite element program ANSYS was used to evaluate the temperature distributions, both steady state and transient, for a squirrel cage motor winding [14S]. A generic three-dimensional thermal model was developed for analyzing the thermal behavior of electric vehicle batteries [37S]. The transient three-dimensional conduction equation with a source term that accounts for the propagating resistive wave front has been solved for a superconducting magnet coil [10S]. Temperatures and current decay have been evaluated during superconducting magnet coil quench [28S].

A review was made of numerical computations of air movement and convective heat transfer within buildings [65S]. The effect of a paint coating on the radiative and convective heat transfer from a surface was investigated by treating the coating as a non-gray absorbing, emitting and anisotropically scattering medium [35S]. Simple models of the coupled heat transfer in a typical light fitting were developed [67S]. The dynamic behavior of a liquid convective diode for space heating of passive solar buildings was explained by theory and experiments [26S]. The general conduction equations were presented and solved for large space structures consisting of bar-like members [56S].

Two papers reported numerical and experimental studies of the heat transfer characteristics of a latent heat storage unit containing a circular-finned tube [22S, 23S]. A one-dimensional numerical model of a single tank for stratified thermal storage included the effects of through-flow conditions, and conduction and turbulent mixing within the water [50S]. The assumption of lumped heat capacity in analyzing a thermal storage system was shown to lead to overestimates of the magnitude of the thermal flux in or out of the storage [59S].

A coupled heat and mass transport model was used to simulate water and heat movement in soil under freezing conditions [34S]. The complex variable boundary element method (CVBEM) has also been applied to the problem of predicting freezing fronts in soils [21S]. A study of the energy balance of drying bare soils indicated that the major errors of using null-point calorimetry to estimate soil heat flux and thermal conductivity are likely to arise from net evaporation in upper soil layers [9S]. A thermal analysis provided information on the effectiveness of open field burning on destroying soil bound microorganisms [6S].

The dynamic response of a single-pass crossflow heat exchanger, with both fluids unmixed, to arbitrary time varying inlet temperatures of fluids was investigated analytically [16S]. Modeling studies compare favorably with experimental results for the performance of a horizontal coil ground-coupled heat pump [7S]. An analytical model of transient, simultaneous heat, water and air transfer was used to study drying front movement near low-intensity, impermeable underground heat sources [8S]. The steady-state rates of heat transfer to a cold horizontal pipeline within an atmospheric pressure, air-filled, horizontal rectangular cavity with relatively hot isothermal walls, have been determined experimentally [3S]. Investigations were carried out to study the boiling heat transfer and flow distributions in an evaporator using an oil–fluorocarbon binary mixture [54S]. In a proposed model of the heat transfer in a liquid–liquid spray column, heat is transferred directly from the dispersed phase to the continuous phase as well as indirectly through the wake [60S].

The high temperature insulating properties of unevacuated horizontal multilayer insulating systems were reported [18S], and two design criteria for optimizing performance were presented [29S]. The insulating ability of a multi-layer insulation system, consisting of a few layers on an aluminum taped 77 K surface, was studied experimentally to understand quantitatively how thermal performance changes with the number of multilayers and vacuum level [58S].

Heat loss and angular momentum decay in a constant volume cylindrical vessel is of interest because the flow has features similar to those in internal combustion engines [63S]. The considerations presented in ref. [4S] lead to a proposed method of analyzing the instantaneous heat transfer between working fluid and combustion chamber and included the influences of the turbulent flow field and radiation. Individual states of heat flux distributions and heat losses of the cylinder head, intake and exhaust valves of each stroke have been determined experimentally for a four-stroke gasoline engine [11S]. The effect of gas temperature on the heat transfer coefficient between the gas mixture and cylinder wall of a four-stroke gasoline engine was studied [69S]. The effects of gas flow (swirl and squish) and fuel spray jet on local instantaneous heat flux on the piston crown of a small size direct injection diesel engine were investigated experimentally [18S]. The piston temperature distribution as a function of engine speed and load was analyzed for a diesel engine [27S]. It was shown that the analysis of heat transfer in tube bundle heat exchangers can be applied with high accuracy in predicting cooling of an inline combustion engine [66S]. Experimental measurements were presented of the fundamental frequency, pulsation pressure amplitude and heat transfer coefficient in a natural-gas-fired pulsating combustor [17S].

Individual papers dealt with a variety of devices. An analytical method was presented for computing the cooling performance and pressure loss in internal convective steam-cooling gas turbine blades of return flow type [48S]. In a study of the heat transfer in an axial compressor casing, a non-uniform distribution of the heat transfer coefficients over the casing segments were observed [39S]. Comparisons were made of the heat transfer coefficients of various oil-cooling systems for commercial-vehicle light machines [12S]. Flow visualization studies were used to help explain the effect of working fluid type on the heat transfer in circular open thermosyphons [68S]. Thin film heat flux gauges and flow visualization techniques were used to investigate heat transfer to the walls of a two-dimensional scramjet combusion chamber [44S]. The temperature rise of a spur gear tooth due to a repeated moving heat source was modeled [47S]. Temperature measurements in full circular bearings show that the maximum temperature increases considerably with increasing speed or lubricant viscosity and with decreasing clearance ratio [42S].

The heat transfer aspects of a wide variety of processes were considered. A numerical simulation was used to analyze the effect of air bubblers on glass-melt circulation and heat transfer in a glass-melting tank [62S]. A numerical simulation of a rotary dryer was described [31S]. The intensity of cooling was measured on three commercial coolers of rubber and the results were interpreted with the aid of a simplified, one-dimensional model [19S]. Temperature distributions in the vortex flow target system of an accelerator breeder reactor were predicted [41S]. In gas-driven hydraulic fractures, as occur in rock blasting and underground nuclear testing, the high temperature gases are radically cooled by heat transfer to the host material [15S].

A mathematical model of heat and mass transfer in the cooking of a meat loaf has been derived [20S]. A dimensionless correlation of the heat transfer coefficient between the barrel wall of a food extruder and the extrudate was presented [38S].

The progress in the development of methods, models, and software for analyzing or simulating the flow of heat in welds was summarized [13S]. The contributions and the importance of the different heat transfer modes during arc welding were assessed [55S]. A mathematical model was developed to predict the velocity, temperature, and current density distributions in inert gas welding arcs [40S]. A method to apply forced convection heat transfer by gas jet impingement to weld metals deposited by the GTA weld process was described [64S]. The problem of steady-state and transient heat transport associated with thin-plate welding was formulated and solved using a finite element method [33S].

Two papers described numerical techniques used to analyze the temperature field in the cutting zone during metal cutting [46S, 51S]. The authors of ref. [5S] addressed the contact thermal problem for a friction pair consisting of tool and structural materials that are in continuous plastic sliding contact. Evaporative cutting of a semi-infinite body with a moving CW laser was considered [43S]. Results were presented of an experimental examination of contact heat exchange during metal forming processes [36S]. An analysis was conducted of the temperature distribution in a tubular specimen subjected to high frequency induction heating [45S]. The convective heat transfer coefficients for cylinders under nozzle fields were determined systematically in a preheating chamber model as a function of the nozzle field parameters for the application of the reheating round billets.

An initial solidification analysis in the vicinity of the meniscus in continuous casting was performed [61S]. Research examined the influence of withdrawal speed and the frequency of mold oscillation on heat transfer through the mold walls [53S].

Transient temperature distributions in human skin and subdermal part exposed to cool environment with negligible perspiration and moderate environment were investigated [57S].

The concept of resonant heat transfer enhancement based on excitation of shear-layer instabilities present in internal separated flows was introduced [52S].

The small-scale structure of forced, turbulent flows developed after Taylor and Kolmogorov was extended to that of buoyancy-driven flows [1S].

SOLAR ENERGY

The U.S. National Bureau of Standards solar collector test program was reviewed and recommendations made regarding the use and limitations of the thermal performance measurements [51T]. An analytical solution is presented for heat transfer in flat plate collectors that accounts for duct design and the thermal developing region [33T]. An analysis is developed for a flat plate air heating collector in which a partial second glazing improves the thermal efficiency for long absorber plates [12T]. Collector efficiency vs Graetz number is given for air flow in the triangular ducts of a V-groove collector [19T]. Simulated performance of a compound parabolic concentrator is compared with corresponding flat plate collectors in which low concentration CPC designs are shown to have superior thermal performance [20T]. Experiments and finite difference numerical analysis are performed to study the effects of eleven design and operating parameters for an evacuated tube collector [40T]. The thermal efficiency of a co-axial heat pipe collector was measured for half-hour periods to determine the effect of mean fluid to ambient temperature difference [4T]. The effect of optical depth on a solar collector in which the solar energy is collected directly by a semi-transparent working fluid was investigated theoretically and experimentally [7T]. A two-dimensional analytical solution is developed which is used to simulate the direct absorption of solar energy within a liquid film flowing downward over a solid wall within a cavity receiver [31T]. Single and two-phase flow heat transfer is studied in the helical absorber tubes at the focal point of a paraboloidal concentrator [49T]. A method is established which can be used to measure complex radiative–convective heat transfer in high temperature solar receivers [36T]. A network heat transfer model is presented which predicts the temperature distribution in terrestrial photovoltaic arrays [24T].

A steady-state method of predicting the monthly thermal performance of solar ponds is compared with detailed hourly numerical simulations [25T]. Good agreement is found for both monthly and annual thermal performance. Heat transfer models for steady and unsteady operation of a shallow solar pond are presented and the results are compared with corresponding experimental data [30T]. The results of a nine month test of a small salt-gradient solar pond are presented [16T]. Experimental temperature and salt concentration measurements are given for various lower convective layer temperatures in 5°C increments [10T]. A comprehensive literature review of double-diffusive effects on solar ponds is made [34T]. One-dimensional numerical simulations are used to determine the optimum thickness of the non-convective zone in a solar pond [8T]. The results indicate that the optimum thickness changes from month to month. The effect on heat loss through various materials below a solar pond is analyzed [9T]. An analytical stability analysis for the non-convective zone of a solar pond is given in which the logarithms of the concentration and thermal gradients are found to be related by a simple equation [11T]. Experiments indicated that instabilities occur at the location of minimum salinity gradient and these instabilities are confined to a narrow region [29T]. Alternate heat removal mechanisms are analyzed which shows that heat extraction can be increased as much as 62% over convectional solar pond heat extraction techniques [32T].

A model is presented for stratified liquid sensible heat storage systems when the fluid enters at the location of zero temperature difference [15T]. Various mathematical models are compared to predict the charging time required for sensible liquid storage tanks [38T]. A storage system is modeled using a random walk procedure to determine the distribution of energy stored [35T]. A study is given in which the geometry and heat transfer rate to a packed bed thermal storage system is analyzed [14T]. Accumulator heat exchangers are studied with applications to solar absorption cooling systems [42T]. The thermal performance of a 30 kW storage unit using polyethylene rods and ethylene glycol was evaluated experimentally [27T]. An explicit one-dimensional finite difference model was employed to simulate the heat transfer characteristics measured in the previous reference [28T]. An experimental study was performed on the heat transfer of calcium chloride hexahydrate surrounding a coaxial water filled heat exchanger pipe [54T]. Two different stacking and baffle arrangements were tested with phase change material rods located under the floor of a solar heated greenhouse [23T].

A theoretical and experimental study of a thermosyphon solar water heater system showed that overall thermal efficiency was higher for a flat plate absorber than a tube-in-sheet absorber [55T]. A theoretical model has been developed to predict the performance of thermosyphon solar water heaters with a heat exchanger in the storage tank under various load conditions [39T]. The lack of thermal insulation on the upper pipe of a thermosyphonic hot water system was found to be very detrimental to system performance as it may result in backflow from the storage tank to the collector [50T]. The thermal performance of a collector array on a residence was determined including the effective array absorptivity and loss coefficient [26T]. Simple analysis of integral solar water heaters were found to be limited in their ability to provide an accurate guide to the thermal performance under actual service conditions [48T]. A lumped parameter model is given for an integral water heating collector which shows good agreement with experimentally measured mean water temperature [56T]. Storage of solar energy in a mixture of sand and iron filings that surrounds a buried water pipe is analyzed to determine the effect of service conditions on the overall efficiency [12T]. A theoretical study of solar thermal storage in the ground is presented with applications to drying [1T].

Activated charcoal and methanol were used to construct a diurnal cycle solar powered ice maker that produced 35 kg of ice on a sunny day with 6 m^2 of collector area [37T]. An analysis is presented of a closed type solar powered adsorption cooling system which showed good agreement with existing experimental data [41T]. A method is devised to model a solar powered absorber–generator to determine the temperature of the absorbent [44T].

A simple algebraic model for evaluation of the average performance of passively heated residences is given which is suitable for both direct gain and storage wall systems [22T]. The development and application of a thermal network model is presented to simulate the thermal performance of passively heated direct gain rooms [3T]. The operating characteristics of a Trombe wall for preheating ventilation air in a farrowing house were measured [45T]. Experimental measurements on a lattice solar wall show that it performs better than a convectional solar wall [53T]. Solutions to thermal networks are given representing simulation of structures with a flat brick roof or a lightweight adobe domed roof with and without moist interior surfaces [5T]. The effect of ventilation air flow rate is found to be significant in passively heated solar structures [47T].

Seasonally dependent correlations are developed to predict the daily ratio of diffuse to total radiation incident on a horizontal surface [46T]. An analytic method is described for calculating daily averages of solar angles and air mass from long-term average data [21T]. A linear correlation between monthly average daily global solar radiation and sunshine duration is presented which agrees with annual values to within 4% [6T]. The distribution of atmospheric aerosol is shown to cause an error in the Langley method of determining the solar constant by up to 3% [43T]. The solar transmissivity as a function of incidence angle is measured with a solar simulator for a variety of materials and coating [17T]. Two models are presented to predict the solar transmission through layers of water and glass representing a stack of glass bottles in a liquid [52T]. Solar radiation propagating through turbid media is modeled analytically to simulate the photon flux through plant tissue [18T]. Relationships between chemical treatments of stainless steel and the optical properties of the coatings are discussed relevant to using the coatings as a solar absorber surface [2T].

PLASMA HEAT TRANSFER

The number of papers related to plasma heat transfer showed a substantial increase during the past year. Many papers dealt with electric arcs and their applications.

The stable configuration of an arc in crossflow is due to heating at the leading edge and enhanced cooling of the trailing section. This is achieved by gradients of ohmic heating and heat conduction across the arc caused by its curvature [48U]. In arcs with superimposed flows, turbulent heat and mass transfer frequently exerts a decisive influence on the shape of the arc and on its energy characteristics [82U]. A semiempirical model of turbulence is proposed for describing the interaction of an electric arc and a turbulent gas flow [4U]. Calculated characteristics of an electric arc burning in a turbulent air flow in a long cylindrical channel are compared with experimental data [3U]. Theoretical studies of the thermal contraction of an arc channel at the anode passing through a turbulent plasma boundary layer, indicate that an instability in the heat balance develops along the falling part of the current–voltage characteristic [36U].

Studies of the physical processes in gas–tungsten arcs (welding arcs) indicate that the addition of 0.1% cerium to an argon arc can lead to marked changes of the arc properties [27U]. Spectrometric measurements of the temperature fields in gas–tungsten arcs using water cooled and molten anodes indicate little temperature variation in spite of anode vapor concentrations of up to 2500 p.p.m. in the vicinity of the anode in the case of a molten anode [21U]. The composition as well as the electric and thermal conductivity of a Cu–air plasma have been calculated at atmospheric pressure for temperatures from 5000 to 14 000 K and for different Cu content. The properties of the plasma change substantially in the presence of metal vapor [61U]. A spectroscopic analysis of the plasma generated by a double-flux tungsten inert gas (TIG) arc torch shows that the plasma is dominated by metallic vapor species in the vicinity of the molten anode, while a nearly pure argon plasma is observed in the cathode region of the arc [14U]. There is a strong correlation between arc voltage and anode erosion in an N_2 arc at atmospheric pressure. Metal vapor in the arc seems to decrease the electrical conductivity resulting in a corresponding voltage increase [68U]. Contamination of an arc plasma by electrode vapor depends strongly on the existence of electrode jets which are responsible for carrying and distributing such contaminants [41U].

A computerized spectroscopic system for analyzing LTE and non-LTE plasmas has been developed with automatic correction for self-absorption [73U]. The magnetic field used to rotate an arc also enhances the spectral lines indicating a non-LTE condition [22U]. An approach is presented for handling radiative transfer in high pressure plasmas where collision broadening dominates self-absorption [83U]. Studies of long free-burning vertical arcs in atmospheric air reveal axis temperatures around 7000 K [47U].

Optical measurements, including spectrometric temperature measurements in SF_6 high-current arcs (up to 2.6 kA) are in good agreement with calculations based on LTE [29U]. Using differential interferometry, the temperature distribution in the upstream and downstream regions of a dual flow orifice nozzle arc interrupter have been measured with emphasis on the thermal boundary layer (arc mantle) surrounding the arc [69U]. Results of investigations of the nozzle ablation process in high-power arc circuit interrupters are reported which include radiative emission and absorption measurements [32U]. Local overheating of the contacts of a circuit breaker may be avoided by designing the contacts so that their magnetic field induces rotation of the arc [30U]. An improved model for circuit-breaker arcs makes it possible to predict the breaker thermal short-circuit interruption performance within the entire range of practical interest [50U]. The observed nozzle ablation in SF_6 circuit breakers is mainly determined by the geometry of the arcing device [53U]. An ablation arc model applied to ablation controlled arcs allows to quantify the phenomena related to nozzle clogging in gas-blast circuit breakers, namely flow blocking and reverse flow heating [71U]. The dynamic behavior of nozzle arcs is governed by the close coupling between the arc and its external flow [20U]. The post-arc heat diffusion from an arc developed due to flash over on open insulation may play a decisive role in the recovering of the dielectric strength of the ruptured gap [78U].

A method has been developed for measuring the net heat flux to a hot evaporating cathode in a vacuum arc with diffuse cathode emission [62U]. A dynamic model of the cool-down phase of an inactive cathode crater of a vacuum arc is used for determining the solidification time for Cu and W taking heat conduction, phase changes, the motion of the melt and surface cooling due to evaporation and radiation into account [66U]. Studies of the spot behavior and of local cathode heating in high-current (900–3000 A) and low-current (20–60 A) arcs show that three different conditions can occur leading to local heat accumulation at the cathode: spot grouping, prolonged spot attachment, and repeated return to previous attachment sites of individual spots [9U]. Investigations of the cathode arc plasma flow in a Knudsen layer show that the evaporation rate in the cathode spot depends on the processes providing the ion flux in the cathode region which is required to maintain the thermal balance of the cathode [6U]. Experimental data of cathode crater formation in vacuum arcs are in good agreement with an analytical model taking phase changes, Joule and ionic heating, electron emission, and mass loss due to evaporation and ejection of molten metal into account [67U]. The dominant erosion mechanism of cathodes in a vacuum-arc centrifuge seems to be via ions which return to the cathode surface across a collisionless sheath [65U].

Experimental studies of arc-generated flow phenomena in repetitively pulsed gas flow spark gaps are in qualitative agreement with analytical studies confirming that heated gas convects at the undisturbed gas velocity [45U]. Based on experimental data, a simple model has been developed which describes the recovery of a spark gap with gas flow [46U]. During the arc phase of an automotive spark in air, the maximum temperature of the arc plasma was found to be 4600 K derived from the slope of the continuum radiation [63U]. Studies of the radial variation of plasma parameters in a pulsed low-pressure (100–150 Pa) arc in He indicate a maximum electron density of $3.3 \times 10^{21}\ m^{-3}$ and a maximum electron temperature of 3.85 eV [1U]. An electric arc heat source may move with speeds comparable to the rate of heat propagation. Results based on a generalized model of this situation show that the largest value of the temperature is reached considerably sooner than by neglecting the inertia of the heat source [39U].

A transferred arc plasma reactor has been used for arc melting, reprocessing, and upgrading of critical materials and alloys [70U]. Besides other heat transfer mechanisms, conditions due to evaporation processes have been included in the analysis of heat transfer by water cooling of wall segments of arc furnaces with emphasis on design criteria not to exceed the critical heat flux [72U]. Studies of the molten metal pool, in a vacuum arc melting furnace indicate that the pool exerts a strong influence on the ingot, especially when melting of titanium alloys from the compacted electrode is considered [31U]. A model has been developed for describing thermoconvective emissions from an open vault arc furnace for determining the proper procedure and dimensioning of a system for capturing and control of fumes, dust, and energy [58U]. A single-roller rapid quenching device with a plasma-arc torch and a water cooled Cu hearth has been developed for rapid quenching of high melting temperature alloys. Amorphous ribbons of $Nb_{80}Si_{20}$, Nb_3Ge, and Ta-(Si, B) alloys have been obtained and amorphous Nb_3Ge showed a superconducting transition temperature of 18.3 K after heat treatment [44U].

Measurements of heat and momentum transfer of powder particles injected into an atmospheric pressure plasma jet arc compared with predicted values [80U]. A simple analytical method, the Z-potential method, is proposed for particle–gas mass transfer calculations under plasma conditions [33U]. Measurements of heat fluxes to spherical models and plane surfaces exposed to plasma jets are compared with experimental results of other authors [16U]. A numerical model describing melting of small particles injected into a thermal plasma jet is used to predict optimal parameters for plasma spraying [26U]. Heat fluxes to a sphere exposed to a two-temperature plasma in the molecular flow regime are independent of the sphere size and approximately proportional to the gas pressure [12U]. Results are presented of a comparison of the effectiveness of heating disperse polymers in gas flames and in plasma streams [37U]. LDA measurements of the velocities of alumina particles injected into a plasma jet reveal values from 20 to 60 m s^{-1} [49U].

Transport coefficients of a chemically reacting plasma in the presence of a magnetic field may be calculated by using the Chapman–Enskog approach. Sample calculations for a potassium-seeded argon plasma are presented [56U]. Calculations of thermodynamic and transport properties of SF_6–N_2 mixtures in the temperature range from 1000 to 30 000 K and pressures from 1 to 10 atm indicate that chemical reactions exert a strong influence on thermal conduction and heat capacities [24U]. The total rate coefficients used in a simplified collisional-radiative (SCR) model have been calculated for thermal nitrogen plasmas at atmospheric pressure [5U]. Significant departures from standard transport coefficients have been found for the electron current and heat flux in a fully ionized plasma with errors up to 65% [18U]. Results based on a model describing the structure of a plane and stationary ionizing current sheath taking radiation transport into account, indicate that radiative losses can be very high, reaching about 30% of the available power [8U]. Effective recombination and ionization coefficients are calculated for optically thin and optically thick non-equilibrium nitrogen plasmas, using a time-dependent approach based on a collisional-radiative model [77U].

A strong vortex producing a 'gas tunnel' for an electric arc proves to be a useful tool for producing high energy density plasma jets [2U]. Temperature measurements in the jet of an inductively-coupled nitrogen plasma at pressures of 0.1 and 0.3 atm confirm previous conclusions that the rotational temperatures are identical with the gas temperature [23U]. High-pressure argon plasmas with temperatures up to 11 000 K have been produced by gas compression. Comparisons with analytical results show the importance of radiation losses and boundary layer effects [34U]. Numerical results of swirl flow cooling in high-heat-flux particle beam targets and swirl-flow-based plasma limiters indicate that local heat fluxes in excess of 7 kW cm^{-2} occur at the water-cooled surface on the side exposed to the beam [55U].

For an Nd-glass laser ($\lambda = 1.06$ μm, $p \sim 10^{16}$ W cm^{-2}) interacting with a plasma ($n \approx 10^{17}$ cm^{-3}), the induced magnetic field is found to be of the order of 100 T, affecting electron thermal conduction and inhibiting heat transport [11U]. Two types of discharge heated longitudinal Sr^+ recombination lasers have been investigated: a low heat loss configuration using input powers of 350 W, and a high heat loss configuration with 1 kW power input to the discharge tube [51U]. Studies are reported on how the effects of deviations from Maxwell–Boltzman electron energy distribution, that are characteristic of heat transport in laser-produced plasmas, could modify the interpretation of such experiments [19U]. Calculated plasma size, peak temperatures, global absorption characteristics, and thermal efficiencies of laser-sustained plasmas in axisymmetric flows are in good agreement with experiments [25U]. Results of a study of laser-sustained plasmas in flowing argon using a pressurized absorption chamber and a 10 kW CO_2 laser indicate a total absorption of up to 80% and thermal conversion efficiencies in the range from 6 to 25%, depending on pressure, flow rate, and laser power [43U]. Quantitative results of another study of laser-sustained plasmas in argon flow clearly indicate that a perceptive analysis of such laser-sustained plasmas must take into consideration the two-dimensionality of both the flow field and the laser energy distribution in the focused beam [35U].

Synthesis of ultrafine SiC powders in thermal arc plasmas reveals a bimodal distribution of the particle sizes with the majority of the particles falling in a size range from 2 to 40 nm [40U]. The nitriding of niobium and tantalum, with argon–nitrogen and argon–nitrogen–hydrogen plasma jets at pressures of 190 and 240 Torr results in higher nitriding rates than those of thermal nitriding at the same temperature [42U]. Chromic oxide decomposition in r.f. argon plasmas shows that the thermal decomposition conversion of Cr_2O_3 into Cr is approximately eight times higher in the homogeneous gas phase than in the solid phase [54U]. Studies of an r.f. silane plasma show that discharge power as well as electrode heating increase the rotational temperature of silane [28U].

For a better understanding of the cathode behavior in an MPD arc jet, a transient heat transfer analysis has been performed based on solutions of the non-linear transient energy equation [52U]. Ion thruster performance can be affected by cooling with liquid nitrogen. Good agreement exists between the temperature-induced effects predicted by a simple discharge model and measured data [81U].

The heat transfer coefficients of parallel-horizontal rows of cylinders exposed to a corona discharge show an increase as the corona current is increased [38U]. An analysis of the conduction-phase characteristics of a hydrogen thyratron plasma is based on the simultaneous solutions of the Boltzmann equation, the rate equations, and the radiative transfer equation [64U]. An explicit solution is obtained for the temperature distribution inside a cylindrical rod with an insulated inner core when the rod is allowed to enter into a fluid of large dimensions with uniform speed, and a simple integral expression is derived for the value of the sputtering temperature of the rod at the point of entry [10U]. Experimental Schlieren images of the non-cylindrical plasma generated by a plasma focus device can be simulated by computers, allowing a quantitative analysis of these Schlieren images, resulting in electron densities and electron density gradients [60U]. A plasma-electrolytic heating mechanism is described in which an active electrode is heated by charged particle bombardment and is cooled by heat transfer with the surrounding liquid via a vapor–gas shell [75U].

Studies of MHD heat transfer in cylindrical geometry with a discontinuity in the wall temperature demonstrate that the temperature falls as the Hartmann number is increased, and convection dominates for large values of the Peclet number [74U]. An exact analysis of a generalized MHD Couette flow is presented, taking Hall currents into account [76U]. Considering a steady two-dimensional MHD boundary-layer flow on a flat plate with a uniform transpiration through the constant temperature plate, it is found that heat transfer at the plate increases with Joule heating, the transpiration number, the magnetic interaction number, and the Prandtl number [13U]. Exact solutions for hydromagnetic boundary layer flow and heat transfer over a continuous, moving, flat surface with uniform suction and internal heat generation/absorption are presented [79U]. Studies of unsteady, free convection flow of an incompressible electrically conducting viscous liquid through a porous plate in the presence of a transverse magnetic field show the effect of various dimensionless parameters on velocity and temperature distribution, the skin friction, and the heat flux [17U].

Studies of the simultaneous effects of the magnetic field, mass transfer and heat transfer on the steady incompressible laminar boundary layer flow of an electrically conducting fluid over a non-isothermal cone show that the magnetic field reduces both the skin friction and heat transfer [15U]. The effects of the magnetic interaction parameters, the electromagnetic loading parameter and the Hall currents have been studied on the laminar compressible boundary layer physical parameters such as the wall shear stress, the heat flux at the wall and the thickness of the boundary layer [59U].

Multiplex CARS temperature measurements in a coal-fired MHD environment indicate maximum temperatures of 2500 K [7U]. The MHD effects on liquid metal cooling of fusion reactors has been experimentally studied with emphasis on temperature fluctuations [57U].

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HEAT-TRANSFER APPLICATION—HEAT PIPES AND HEAT EXCHANGERS

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