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Heat transfer—a review of 1987 literature

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INTRODUCTION

THIS REVIEW surveys papers that were published in the English language literature during 1987 covering various fields of heat transfer. The literature search was inclusive, however, the great number of publications made a selection in some of the review sections necessary.

Several conferences were devoted to heat transfer or included heat transfer topics in their sessions during 1987. They will be briefly discussed in chronological order in this section. An *International Symposium on Cooling Technology for Electronics Equipment* was sponsored by the Pacific Institute for Thermal Engineering and held in Honolulu, Hawaii, 17–21 March. Five sessions dealt with topics like air cooling, liquid cooling, conduction cooling, thermal analysis and computer modeling, and thermal systems problems. The International Centre for Heat and Mass Transfer organized a special *International Seminar on Transient Phenomena in Multiphase Flow* in Dubrovnik, Yugoslavia, on 24–30 May with sessions on wave phenomena in two-phase flow. The majority of papers are being published in bookform by Hemisphere Publishing Corporation. The *32nd ASME International Gas Turbine Conference and Exhibit* was sponsored by the International Gas Turbine Institute of the Society of Mechanical Engineers and was held on 31 May–4 June in Anaheim, California. Four sessions were devoted to coolant side heat transfer, special topics in gas path flow and heat transfer, and discrete hole film cooling. Technical papers are available from the ASME Publication Department. Several Canadian organizations in industry, university, and research held the *5th International Conference on Numerical Methods for Thermal Problems* in Quebec, Montreal, on 29 June–3 July. The *24th ASME/AIChE National Heat Transfer Conference and Exhibition* covered topics like liquid natural gas heat transfer, compact heat exchangers, building heating and cooling load estimating, advances in thermal analysis and control of electronic equipment, and experimental methods in heat transfer in 59 sessions. David Butterworth presented the Donald Q. Kern lecture on the topic "Technology for Process Heat Transfer—Today and Tomorrow" and received the Donald Q. Kern Award. Raymond Viskanta presented the Max Jakob Memorial Award lecture entitled "Melting and Solidification of Metals" and received the Max Jakob Memorial Award. The conference was jointly organized by the American Society of Mechanical Engineers and the American Institute of Chemical Engineers. ASME sponsored papers are available in preprint and volume form from the ASME Order Department, the AIChE sponsored papers are published as Volume 83, Number 257 of the AIChE Symposium Series. The *XIXth International Symposium on Heat and Mass Transfer in Gasoline and Diesel Engines* of the International Centre for Heat and Mass Transfer was held on 24–28 August in Dubrovnik, Yugoslavia. Nine sessions dealt with engine heat transfer, vaporization and sprays, external heat transfer, ignition and quenching, measurement techniques, and numerical flow simulation. The proceedings are available in book form from Hemisphere Publishing Corporation. The *International Symposium on Plasma Chemistry* held in Tokyo, Japan, from 31 August to 4 September 1987 featured a number of sessions related to plasma heat transfer. The papers presented at this conference are published in four volumes (Proceedings of the ISPC-8, Tokyo, 1987). The *1987 ASME Cogen-Turbo International Symposium* covered in one of its sessions experimental flow survey in gas turbines, hot particles in transpired laminar stagnation zones, and erosive particles in power plant draft systems. The symposium was held on 2–4 September in Montreux, Switzerland. The *1987 Tokyo International Gas Turbine Congress* held in October 1987, sponsored by professional societies in Japan, France, China, England and West Germany, included in its program papers on heat transfer. This also was the case at the *IX Brazilian Congress of Mechanical Engineering* held in Santa Catarina, Brazil, on 7–11 December. The *Vth International Conference on Fluid Flow and Heat Transfer* held in Torino, Italy, devoted its program to fluid flow and heat transfer in single and two-phase systems and in nuclear engineering as well as to experimental techniques and new technologies in heat transfer. The *108th ASME Winter Annual Meeting* was held on 13–18 December in Boston, Massachusetts. Heat transfer was covered in 28 symposia, 2 panel sessions and a number of general and poster sessions covering all fields of convective and radiative heat transfer and applications. An invited lecture at the heat transfer luncheon was presented by David Roeffler on the topic "Impact of Lasers in the Manufacture of Automobiles". The Heat Transfer Memorial Award was presented at the same luncheon to Ralph L. Webb and M. Necati Özisik. The Robert Thurston lecture was given by Simon Ostrach on the topic "Transport Phenomena in Industrial Processes".

A large number of books became available during the past year. They are listed in the reference section. Some new journals also started publication.

The following *highlights* characterize interest and studies in heat transfer during the past year.

As a general remark it is noted that applied studies of industrial processes occupy a larger fraction of the heat transfer literature than in previous years.

A number of papers dealing with *conduction* discussed hyperbolic conduction, conduction in composite media and thermoelasticity.

A large fraction of the papers in the category of *channel flow* dealt with separation regions created, for example, by ribs in pipes or blocks in parallel-plate channels. Some simulated electronic module cooling, many investigated enhancement by rib roughening and others give details of sudden expansion or contraction flows. Other major sub-categories in channel flow include variable boundary conditions and papers considering fluids with special properties; examples are helium II or coal slurries. Papers on oscillation or unsteadiness effects and others describing swirl or rotation effects grew in number, whereas the number of conjugate heat transfer papers appeared to decrease.

A noteworthy increase in activity occurred in *boundary layer and external flows*, especially under unsteady conditions. Examples include unsteady laminar, transitional and stagnation flows and unsteadiness due to thermal boundary conditions, both time varying or those that impose instabilities to the flow. High speed flow heat transfer remains an active area especially in studies related to the Orbiter flight. Papers which document turbulence fundamentals are frequently found, although chaos theory, a topic receiving heavy press coverage, has not yet appeared. A large subset of investigations in external flow deals with the effect of special geometry. Cavity and rib-roughened flows are examples. A number of studies considered crossflow over single cylinders and through banks of tubes.

Techniques using radiative emission and absorption for temperature measurement and new developments in calorimetry are included in the sections on *experimental techniques and instrumentation*.

In *internal natural convection cooling*, there is great emphasis on Marangoni convection where variations in surface free energy at a liquid–gas or liquid–liquid interface drive the convection. Such flows are important under conditions in which rotational forces are small and in shallow layers. Related to this is an emphasis on buoyancy and Marangoni driven convection for crystal growth for the manufacturing of electronic components. There is also considerable interest in high Rayleigh number convection where the character of turbulent flow is studied.

External-natural convection from a vertical plate continues to receive considerable attention. Discrete heat sources, wavy surfaces, non-Newtonian fluids, and turbulent flow were investigated. Mixed convection was studied for a variety of geometries including vertical, inclined, and horizontal flat plates, horizontal channels and vertical tubes and cylinders.

Film cooling continues to be of interest and is included in the section on *combined heat and mass transfer*. Also reported are a number of studies on impingement heat transfer processes with application to a wide variety of problems; basic mechanisms for such flows are being studied.

Several models were proposed to describe *condensation* processes on externally finned horizontal cylinders. Surface tension, gravitational force, fin base fillet radius, and fin spacing were incorporated into the models. A variety of direct contact heat transfer processes were also investigated.

Interest in the study of *radiative heat transfer* coupled with conduction and/or convection is very strong. There is also a notable increase in the attention given to the role of radiative heat transfer in combustion systems.

In the area of *numerical methods*, emphasis is on new formulations of combined convection and diffusion and on new methods of calculating fluid flow. Finite-difference and finite-element methods are actively being developed and used.

Expansion is reported on experimental methods, established and new, for the measurement of *transport properties* for natural and synthetic materials—for instance: bulk polymers, thin films [tellurium], soils, dispersed materials, coal ash insulating materials, graphite, liquids [alcohol and aldehyde families], composite metals, magnetic fluids, food grains and frozen foods.

Considerable attention was given to the performance of heat transfer surfaces of *heat exchangers*, to local characteristics of flow and heat transfer, to fluctuating or transient response, and to the synthesis of heat exchanger networks. A considerable number of papers, analytical and experimental, are concerned with *heat pipes* and thermosyphon systems.

The thermal performance of collectors of *solar energy* was studied experimentally and analytically for a number of designs. Other system components have also been studied including solar ponds, sensible thermal storage tanks and passively heated buildings.

Studies of thermal *plasma heat transfer* have been particularly concerned with plasma processing and electric 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 each 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 applications—heat pipes and heat exchangers, Q
Heat transfer applications—general, S
Solar energy, T
Plasma heat transfer and MHD, U.

CONDUCTION

Basic problems

A number of papers which appeared in 1987 approached classical heat conduction problems in interesting ways. The effect of a continuously distributed heat source in a one-dimensional rod can be exactly cancelled either by a continuously distributed sink or by appropriate control of boundary temperatures [7A]. A variational treatment was presented of quasi-stationary heating of a flat plate (one surface temperature increases at a constant rate while the other is insulated) [49A]. An asymptotic solution was developed for the temperature of a semi-infinite cylinder with zero initial temperature, the base of which is heated in a prescribed manner while the curved surface is linearly cooled [29A]. The same geometry was treated, but with prescribed initial temperature, azimuthally symmetric base heating, insulated curved surface and variable thermal conductivity [47A]. A systematic method was proposed for solving time-dependent problems in a plane with mixed boundary conditions [9A]. An approximate technique was presented for solving initial-boundary value problems using a generalization of the fictitious sources method [50A]. Basic analytic techniques for solving mixed boundary value problems were surveyed, with a discussion of relationships among the different approaches [20A, 21A]. The direct operational method was applied to transient heat flow between a solid body generating heat and a fluid [27A]. A procedure was presented for obtaining an approximate solution to the problem of two-dimensional steady-state conduction through a network of thermal bridges [48A]. Galerkin's method was shown to yield a reasonably accurate approximation to the conduction solution for simple geometries [40A]. The cooling of canned beverages was studied in an investigation of conduction in a cylinder containing a pure fluid which may be undercooled [34A].

Fins

Analytical solutions were obtained for fins with uniform and non-uniform heat generation and with variable heat transfer coefficient [53A]. The optimum profile for a longitudinal fin was discussed [46A]. Uniform-area radiating fins were treated by an extension of the method of asymptotic analysis [13A]. A straight fin in which both the base temperature and the environment temperature oscillate was analyzed [38A]. New correlations were presented for determining the thermal interfacial resistance in compound cylinders and finned tubes [28A], and bond resistances in high-finned tubes were evaluated [51A].

Irregular geometries

An approximate solution to problems with irregularly shaped boundaries and variable properties can be obtained using the Galerkin method; this approach can be extended to problems which have regular geometries but other complications which prevent exact solutions (e.g. phase change) [16A, 17A]. Optimal positioning (from the heat transfer viewpoint) of a set of parallel tubes embedded in an arbitrarily shaped two-dimensional enclosure was derived using a boundary integral method [39A]. The general problem of transient two-dimensional heat conduction in a body with moving boundaries was solved approximately using the Galerkin–Kantorovich method [52A].

General non-linear problems

The asymptotic behavior of a one-dimensional transient system governed by a semi-linear heat equation with strong thermal absorption was investigated [11A]. Potential-well theory was applied to determine the existence of solutions to problems with a non-linear boundary condition [30A].

Heat balance integral

The usual heat balance integral approach approximates a temperature profile as a polynomial. A hybrid profile with a claimed improvement in accuracy was presented, in which the profile was represented as the sum of a polynomial and an exponential [54A]. The heat balance integral method was used to study laser-ablation profiles in graphite [22A].

Hyperbolic conduction

The hyperbolic conduction equation was derived based on irreversible thermodynamics and on relaxation processes occurring in a solid under external perturbation [26A]. Hyperbolic conduction in composite media was studied [10A]. A solution was presented to the hyperbolic problem of a semi-infinite medium subject to periodic on–off heating (e.g. with picosecond–nanosecond pulses, as in laser irradiation) [12A].

Composite media

Conduction in composite media continues to receive considerable attention. Periodic heating/cooling of composites with any number of laminates was approached by a new numerical–analytical method [18A]. A perturbation method was applied to analyze a periodically layered composite [15A]. Microperiodic composites were discussed [33A]; see also ref. [55A]. The Kantorovich orthogonal technique was used to construct coordinate systems for analyzing unsteady conduction in multilayer plates [24A]. Steady heat transfer through a plane wall containing a thin cylindrical inclusion of high thermal conductivity was studied [5A]. Transient conduction in laminated binary materials was investigated using numerical inversions of Laplace transforms [45A]. An interesting problem which appears in various physical systems is that of conduction through a medium consisting of a two-phase dispersion bounded by a wall. This situation is considered in ref. [4A], which discusses conduction from an isothermal wall to a suspension of monodisperse spheres. See also refs. [10A, 35A].

Inverse conduction

A general discussion was presented of the inverse conduction problem [36A, 37A], and a spline approximation for the inverse conduction solution was presented [1A]. The solution uniqueness of an inverse problem was investigated [44A].

Thermoelasticity

Transient conduction in a one-dimensional thermoelastic layered composite was analyzed as a nonlinear eigenvalue problem [35A]. The Laplace transform technique was used to analyze thermoelastic waves in a transversely isotropic medium with a cylindrical hole [43A]. A three-part study of thermal effects in rolling/sliding contacts in elastohydrodynamically lubricated disks included experimental and analytical investigations [8A, 25A, 41A, 42A]. Conduction through thermoelastic micro-periodic composites was modelled based on theorems of non-standard analysis [55A]. The problem of heating a large body to a prescribed temperature while avoiding damage due to thermoelastic stresses was studied [19A]. The effect of thermoelastic coupling on the propagation of Rayleigh–Lamb waves in an infinite plate was discussed [6A]. The problem of the effect of a thermal flux on the surface of a thermoelastic half-space was considered [3A].

Friction heating

Sliding contact of two materials generates heat due to friction and/or Joule heating. The problem of predicting the temperature at interfacial contact spots was considered [25A]. Heat transfer between two bodies which are both moving and which have contact over a finite stationary area was studied [56A]. For short times it was shown that heat transfer to the ambient medium could be neglected in analyzing frictional heating of bodies of simple shape [2A].

Miscellaneous

The thermal stability of Landau slabs with variable thermal conductivity [31A] and of hollow spheres with internal heat generation [32A] was examined. Steady-state conduction in stagnant beds of solid particles was investigated, particularly the influence of the bounding walls on the variation of the voidage [23A]. The cooling of superconducting materials subject to a point heat source was modeled [14A].

CHANNEL FLOWS

The expression for the turbulent Prandtl number obtained from the renormalization group procedure was used to describe the process of heat transfer in turbulent pipe flow [98B]. The results were compared with experimental data. Hydrodynamics and heat transfer were discussed for a volume of uniform liquid with induced turbulence [105B]. A multielement hot-wire anemometer system designed to measure the fluctuating velocity and temperature in non-isothermal flow was introduced [9B]. The performance of the system was evaluated by comparing velocity and temperature statistics measured in an equilibrium turbulent boundary layer flow. A method for heat transfer enhancement by selectively intensifying a specific component of the fluctuation energy was suggested [103B]. It was proven that the normal component of the fluctuating energy is intensified selectively by vortex stretching, and that, associated with this intensification, the production of turbulent heat flux increases.

Results of an experimental investigation to determine the effect of geometrical nonuniformities in arrays of rectangular modules deployed along one wall of a parallel-plate channel were presented [78B]. It was observed that heat transfer coefficients on two modules siding a tall module display the highest enhancements. Heat transfer characteristics on a smooth, heated surface, opposite to roughness elements on an insulated wall, were experimentally determined by flowing air through a parallel-plate duct and by changing the shape of the roughness elements [33B]. The effects of acceleration and turbulence, produced on the smooth heated surface, were different for each shape of roughness element. Experiments were carried out to examine the effects of roughness of an insulated wall opposite a smooth, heated plate with air flowing through a parallel-plate duct [34B]. Acceleration and turbulence produced by the roughness elements contributed to an increase of heat transfer on the smooth, heated plate. Enhancements of heat transfer inside of a tube by means of three-dimensional ribs of a regular triangular shape arranged in in-line [47B] and staggered [48B] manners were discussed. Hot-wire measurement and flow visualization results were presented. Numerical results were reviewed for separated, laminar forced convection flow near surface-mounted ribs [32B]. The average Nusselt number in the vicinity of the rib was shown to be a function of Reynolds number and aspect ratio and can be correlated by an equation written in terms of these two. Experimental data were presented for heat transfer to air from the inner surface of an annulus [1B]. Information was also provided on the heat transfer from one side of a rectangular duct to an internally flowing fluid. Arc-shaped turbulence promoters along the inside surface of a circular tube were proposed for enhancing heat transfer performance [29B]. The arc-shaped promoter was found to have the lowest pressure loss of several promoters tested. The turbulent flow structure in a pipe with inclined cascade turbulence promoters was studied experimentally [28B]. The mechanism of secondary flow generation was discussed for various Reynolds numbers. A new heat transfer promoter was devised which was composed of a row of thin plates twisted by 90°, alternating in different directions [3B]. As the flow proceeds along the twisted plates, many axial vortices are produced and flow separation occurs at the lateral edge of each plate. A finite-difference solution to the problem of an abrupt, asymmetric enlargement of a parallel-plate channel was presented [80B]. The solutions of the program, written for a PC, were compared with prior numerical solutions and served to extend the range of investigations of enlargement-type flows. Heat transfer downstream of an axisymmetric abrupt expansion in a pipe in the transition Reynolds number regime was investigated experimentally [7B]. Interesting behavior may be associated with flow instabilities in sudden expansions. Experiments were performed to investigate the axial distribution of the mass transfer coefficient downstream of an abrupt contraction in a flat rectangular duct; a forward-facing step [24B]. The axial distribution of the Sherwood number increased at first (downstream of the contraction), attained a maximum, then decreased monotonically to a fully-developed value.

The flow in the entry region of a heated, curved pipe was analyzed [65B]. Buoyancy disturbs the symmetric secondary motion induced by curvature, the deviation depending on the type of thermal boundary condition. Measurements of velocity characteristics of flows in curved diffusers of rectangular cross-section with C- and S-shaped centerlines were presented [71B]. Related wall heat transfer coefficient measurements were also discussed. Photographs were presented for secondary flow patterns in a straight tube downstream of a 180° bend and in an isothermally heated horizontal tube flow with free convection effects [13B]. The secondary flow patterns were presented for future comparisons with predictions from numerical solutions. Secondary flow patterns at the exit of a 180° bend were presented to illustrate the combined effects of centrifugal and buoyancy forces in the hydrodynamic and thermal developing region of an isothermally heated, curved pipe [14B]. The results were proposed for the assessment of the limit of applicability of existing correlations. A report of convective heat transfer data for turbulent flow around a U-bend was given [8B]. Strongly non-uniform Nusselt numbers persisted for six diameters downstream of the bend, even though secondary flow and streamline curvature were negligible there.

Characteristics of a well-developed, steady, laminar flow in various wavy sinusoidal channels were numerically investigated [58B]. A numerical model based on a finite-element method was used to estimate heat transfer between a solid and a fluid flow through an interface, as encountered in periodically corrugated channels [52B]. In a similar numerical study, characteristics of wavy-wall flows, such as flow impingement on the walls, separation at the bend corners, flow reattachment and flow recirculation were discussed [2B]. This study was extended to a channel flow with fins inserted at bends in the channel. A finite volume methodology was developed for predicting fully-developed heat transfer coefficients, friction factors and streamlines for flow in a corrugated duct [4B]. The performance of the corrugated duct was compared with that of the straight duct under three different constraints, fixed pumping power, fixed pressure drop, and fixed mass flow rate.

An experiment made for studying momentum and mass transfer in straight, round channels and coils was described [66B]. Local and integral hydrodynamic and mass transfer characteristics of flows were measured by an electrodiffusion gage. The effects on heat transfer of two types of internal helical elements built into a cylindrical tube were investigated experimentally [44B]. Results were presented of an experimental investigation of a spiral spring coil used for tube-side heat transfer augmentation [15B]. This spiral spring insert increased the tube-side heat transfer coefficient significantly. A second-law analysis was made on swirling flow in a cylindrical duct [59B]. Conclusions were drawn about the influence of inlet swirl on irreversibility. The problem of heat and mass exchange and friction in the initial section of a pipe with stream swirling was solved [96B]. A method of correlating heat transfer characteristics was presented for thermally-developing laminar flow in a smooth tube with a twisted-tape insert [67B]. A procedure for the implementation of the final correlative equation was presented. An experimental study was conducted to determine local heat transfer performance of flow through two parallel heated disks [55B]. Three distinct heat transfer mechanisms were disclosed along the flow passage: steady laminar, periodic laminar, and turbulent. Local heat transfer on the outer surface of turbine blades was studied experimentally [68B]. The effectiveness of film cooling on the convex and concave surfaces of blades was shown.

A study of fluid flow and mass transfer for oscillatory flow was carried out in wavy channels [63B]. The wavy channels yielded a large mass transfer enhancement as compared with the corresponding straight channel. Fluid flow and heat transfer in a two-dimensional miter bend were examined in connection with a corrugated wall channel [99B]. Unsteady motion due to the instability of the flow downstream of the bend was computed. An exact analytical solution was developed for transient conjugated heat transfer in the thermal entrance region of a parallel-plate duct when the unsteadiness is induced by a sudden change in temperature of the ambient fluid outside the duct walls [87B]. The standard, quasi-steady approach was shown to be appreciably in error for a wide range of conjugation parameter values. Unsteady thermal entrance heat transfer was investigated for laminar duct flows with wall suction and injection [45B]. It was shown that, for forced convection in slow laminar flow in a channel with uniform heat addition, the effect of flow oscillations will be to reduce the channel heat transfer coefficient [75B]. Flow oscillations induce a heat flow back toward the channel inlet. A flexible start-up insert in the form of a rigid flag hinged on a diametral rod was found to enhance heat transfer in turbulent flow in a tube [21B]. Heat transfer over a tube length was enhanced up to three times relative to that for the empty tube. Periodically oscillating unsteady turbulent flow in a channel with turbulence promoters was studied experimentally [30B]. The heat transfer coefficient was slightly enhanced by the flow oscillation. Numerical calculations were presented which show the effect of heat spreading in the wall on non-steady turbulent heat transfer [26B]. Approximation formulae were proposed which enable heat transfer characteristics to be calculated with complex laws of change in temperature at the outer surface of the tube wall.

A solution of the problem of heat transfer between a press-contacted aluminum pin and a ceramic substrate was computed [92B]. The technique has been used in the cooling of microchips. The flow in planar and annular squish gaps of internal combustion engines at the near end of the compression stroke was analyzed [84B]. Steady incompressible stagnation point heat transfer analyses were found to correlate the experimental data satisfactorily. A numerical study concerning the effects of non-uniform heating on the heat transfer of a thermally undeveloped gas flow in a horizontal rectangular duct was presented [41B]. The heat transfer rate and drag increased with the secondary flow due to buoyancy. Results of an experimental investigation of developing local convective heat transfer in triangular ducts with square ribs were presented [53B]. An appraisal of the methods of presentation of results for turbulent flow and heat transfer in straight non-circular ducts was made [27B]. Results of an analysis of fluid flow and heat transfer in annular sector ducts were presented [76B]. An analysis and measurements were made of momentum and heat transfer from fully-developed turbulent flow in an eccentric annulus to inner and outer tube walls [64B]. An experimental study using a hot-wire anemometer was conducted to investigate fully-developed turbulent flows within ducts of a cross-shaped cross-section [60B]. The flow field acquired a high degree of symmetry in this geometry in all planes of symmetry.

The effect of initial nonuniformity of the velocity profile, generated by an upstream elbow, on the quantitative relationship between the heat transfer and friction coefficients in straight ducts was described [10B]. Reynolds' analogy does not hold in this situation. A combined experimental and analytical numerical investigation was carried out for turbulent flow in a flat, rectangular duct with streamwise non-uniform heating at one of the principal walls [81B]. Adiabatic zones periodically inserted between isothermal heated zones were studied. A solution methodology based on integral equations was presented for the problem of heat transfer to laminar duct flow subjected to an axial variation of the external heat transfer coefficient [95B]. Results were calculated for the cases of a stepwise periodic and a harmonic variation of the heat transfer coefficient for both fully-developed laminar flow and slug flow. Combined convection flow in square, circular, and semicircular ducts was numerically studied for axially-nonuniform heat flow [43B]. For the case of the square duct, dual solutions were obtained where the secondary flow was characterized either with two or four vortices. The unsteady thermal entrance heat transfer problem was analyzed by the instant-local similarity method for the region of the porous wall which permits uniform suction or injection and with a step change in ambient temperature [100B]. The extended Graetz problem was analyzed by functional analytic methods [46B]. The proposed computational procedures were more efficient than the separation of variables method and could be used without shooting. The characteristics of transient heat transfer in the combined entrance region of turbulent pipe flows resulting from a step change in the ambient temperature were numerically investigated by a fully-implicit finite-difference numerical scheme [101B]. Attention was given to the influences of the independent groups on the unsteady variations of Nusselt number. Thermal development of a hydrodynamically-developed turbulent flow in an isothermal-walled circular tube was investigated in complementary numerical and experimental studies [83B]. The experiments used the naphthalene sublimation technique. Numerical solutions for a vorticity–velocity method were presented for combined free and forced laminar convection in the thermal entrance region of a horizontal rectangular channel [16B]. The large Prandtl number assumption is valid for $Pr = 10$ when $Ra < 30\,000$ but for a larger Prandtl number when the Rayleigh number is higher. Entry-region hydrodynamic and thermal conditions were experimentally determined for laminar mixed-convection water flow through a horizontal rectangular duct with uniform bottom heating [35B]. Hydrodynamic instability resulted in breakdown of mushroom-shaped longitudinal vortices and subsequent transition to turbulent flow. Thermal entrance region heat transfer results were presented for an isothermal-walled tube for two types of turbulent velocity distributions: developed velocity and velocity developing from a sharp-edged inlet [82B]. Experiments and numerical studies of the separation of a smooth attached buoyant flow from the inner wall of a duct, as the duct discharges into a quiescent environment, were reported [57B]. Downward flow into cold air near the wall of the duct leads to premature separation of the wall boundary layer. The separated boundary layer merges into the buoyant jet above the duct exit.

Naphthalene sublimation experiments were conducted to study the effects of the pin configuration, pin length-to-diameter ratio, and entrance length on local endwall heat/mass transfer in a channel with short pin fins [42B]. Overall and row-averaged Nusselt numbers were presented. The analysis of flow and heat transfer in the entrance region of concentric circular annular ducts was presented [69B]. Measurements were made of the combined natural convection and radiation heat transfer from a horizontal finned tube situated in a vertical channel open at the top and bottom [79B]. The heat transfer coefficients were found to be lower with the thermally conducting wall in place, but only moderately. Fluid flow and heat transfer in two-dimensional finned passages were analyzed for constant property laminar flow [38B]. The fins were found to cause the flow to deflect and impinge upon the opposite wall so as to increase the heat transfer significantly. However, the associated increase in pressure drop was an order of magnitude higher than the increase in heat transfer.

A study was carried out in order to understand the combined forced and free convective heat transfer characteristics in a narrow vertical rectangular channel heated from both sides [88B]. The results apply to the thermal–hydraulic design and the safety analysis of research nuclear reactors. An experimental study was performed on concentric annular gas flow with the inner tube heated [90B]. Criteria for the occurrence of so-called laminarization of the annular flow were given. A method was developed for calculation of heat transfer in tubes to turbulent gas flows with large thermal loads and moderate or low input Reynolds numbers [40B]. Laminarization was described. Flow of a compressible fluid from a pressure reservoir through a pipe with constant circular cross-section and constant pipe-wall temperature was investigated [54B]. Heat transfer measurements were carried out in a flow with a discontinuously shear-thickening fluid [51B]. It was found that this peculiar fluid is a heat transfer reducer. Momentum and heat transfer in inelastic non-Newtonian fluids flowing through coiled tubes was discussed [37B]. The effect of dissipation on convective heat transfer in flow of non-Newtonian fluids with constant properties over non-isothermal surfaces was analyzed [74B]. Certain cases where dissipation made a significant contribution to heat transfer were discussed. The results of an experimental study of heat transfer to power-law fluids flowing in a cylindrical tube were compared with the results of a numerical simulation program [22B]. The effects of wall conduction on the rate of heat transfer from a finite length, thick-wall tube were presented [91B]. An approximate method was used to find the solid–fluid interface temperature. An investigation of the heat transfer occurring in a pseudoplastic fluid flowing through a rectangular channel was presented [77B]. The importance of secondary flows induced by the thermal gradient in the cross-section was shown. A study of rates of heat transfer to non-Newtonian fluid foods passing through horizontal tubes of circular cross-section under laminar flow conditions was given [70B]. Developed isothermal laminar flow of a non-linear viscoelastic fluid in a double annular channel was considered [104B]. Expressions were presented for determining the critical Saint-Venant numbers at which choking of one of the channels occurs. Heat transfer to supercritical water was analyzed [50B]. Focus was on the mechanisms of heat transfer deterioration. Heat transfer in the critical regime of mixtures was discussed [19B], and criteria for predicting deteriorated heat transfer conditions for water at supercritical pressure were given [49B]. Heat transfer measurements of a channel containing He II were reported [12B]. The configuration was a rectangular cross-section channel heated uniformly over its length and open at both ends so that natural circulation could occur. A mathematical model to simulate the cool-down behavior of a warm transfer line using liquid helium in a microgravity environment was proposed, and thermal–hydraulic characteristics of different possible flow regimes which may occur during the cool-down process were discussed [61B]. Experimental results were presented on the forced convection heat transfer to supercritical helium flowing downward in a vertical stainless steel tube [36B]. A discussion on heat transfer deterioration in the supercritical region was also given. A derivation of the lubrication equation suitable for a non-linear rheological model was presented [97B]. It was concluded that both the temperature rise and non-Newtonian character of the oil film should be considered in the elastohydrodynamic analysis. A numerical model was described for calculating lateral and downstream mixing of contaminant species in two-dimensional confined flows [85B]. The model was used to study species mixing. A model was developed to investigate the recycle effects on heat and mass transfer through a parallel-plate channel [102B]. The results showed that recycle at the ends has a positive effect on the heat and mass transfer. Laminar heat transfer coefficients for a round tube flow of highly loaded coal–water mixture were measured [94B]. It was found that when the slurry temperature exceeded 100°C augmentation of the heat transfer was observed. A quasi-one-dimensional hydrodynamic model of gas–vapor–liquid dispersed annular flows in a round tube was considered [62B]. Results of experimental studies on the determination of forced interaction and rates of moisture exchange between the flow core and liquid film were analyzed. Results from an experimental study of the heat transfer crisis in the boiling of water in vertical steam-generating channels capped on the bottom were presented [6B].

Heat transfer and pressure drop characteristics of a converging–diverging duct with rounded corners were determined numerically [5B]. The heat transfer rates were relatively insensitive to the presence of rounded corners. A control volume finite-difference approach for the solution of axisymmetric laminar viscous flow through a converging–diverging pipe was presented [25B]. A finite-difference scheme was utilized to predict periodic fully-developed heat transfer and fluid flow characteristics in a converging–diverging flow channel [20B]. Moderate enhancement in Nusselt numbers occurred at higher Reynolds numbers when compared with corresponding values for straight ducts. Enhancement surfaces, with many holes, bent in a trapezoidal shape were evaluated [72B]. A duct constructed with these surfaces has enlargement and contraction parts alternately along the flow passages. The heat transfer coefficient of the new duct increased by about three times that of a duct with plain surfaces at the same Reynolds number. Heat transfer to laminar flow in tapered passages was studied for two types of thermal boundary conditions: prescribed heat flux on both walls and on one wall with the other wall adiabatic [73B]. Constant heat flux boundary conditions for converging flow yielded a reduction in Nusselt number.

A method for calculating heat transfer and friction of internal turbulent flows with longitudinal pressure gradients was discussed [39B]. Local mass transfer rates at walls of pipes downstream of constricting nozzles were measured using the electrochemical limiting diffusion current technique for different electrolyte Schmidt numbers [17B]. Evidence of the highly turbulent flow was found in the recirculation zone near the position of peak mass transfer.

Results of measurements of velocity and temperature fields and surface friction integral heat transfer under conditions of stable and unstable density stratification in a flat channel were presented [93B]. Separation of a slow moving flow at the lip of a duct emerging into a quiescent negatively buoyant environment was discussed [56B]. Results showed that the channel flow separates at shorter distances from the entrance as the Froude number is reduced.

A method of estimating the gas-phase mass and heat transfer coefficients for turbulent gas streams in cylindrical wetted-wall columns was proposed and compared with experimental data [31B]. A calculation method, which includes natural convection, transition and the onset of separation, was presented for heat transfer in vertical duct flows [11B].

A numerical finite-difference solution was given for the problem of unsteady, laminar, forced convection heat transfer in a parallel-plate duct with finite thermal capacity walls which interact with a medium outside the duct [86B]. Comparisons were made with the zero thermal capacity wall solution and with quasi-steady results. An analysis was conducted numerically for an internally finned tube which serves as the inner tube of a double pipe heat exchanger [89B]. Transient forced convection for slug flow inside parallel-plate channels and circular ducts including conjugation to the walls was solved analytically and exactly for periodic variation of the inlet temperature [18B]. The amplitude and phase lag of oscillations with respect to the conditions at the inlet were determined for the wall temperature, fluid bulk temperature and heat flux. A numerical analysis was carried out for turbulent, forced convection heat transfer to water flowing inside a fouled tube which was locally heated with uniform heat flux from the outer surface [23B]. Heat flow within the tube wall in the upstream and downstream directions was found to be significant.

BOUNDARY LAYER AND EXTERNAL FLOWS

A similarity solution method was presented for laminar forced convection heat transfer from either an isothermal surface or a uniform-flux boundary [46C]. The results can be integrated to give solutions over the full range of Prandtl numbers. Similarity laws were discussed and compared with experimental and numerical results for strongly heated or cooled flat plates [56C]. Mass transfer rates in laminar and turbulent non-separated flows were asymptotically expanded for small diffusivity coefficients [72C]. The results were shown to agree well with data for mass transfer in tubes, packed beds and fluid–fluid contractors.

The dynamics of a passive scalar in three-dimensional isotropic turbulence was studied with the aid of the Markovian statistical theory [45C]. The decay rate of temperature variance was evaluated. The Langevin model for the velocity was used to develop a model for passive scalars in turbulent flows [69C]. Comparison is made with measured velocity–scalar correlation coefficient profiles. A unified model for interface solid–turbulent fluid heat and mass transfer was discussed [36C]. An extension to non-Newtonian fluids was included and applicability of the model was tested using data for granular beds and stirred tanks. Space–time spectra of velocity and temperature fluctuations were analyzed by means of a hierarchic model of two-dimensional turbulent convection [22C]. The spectra contain a quadratic relationship between the frequency at which a peak occurs and the number of the peak. An artificially generated turbulent spot was investigated experimentally in a heated boundary layer using a rake of minithermocouples [25C]. It was shown that when two spots are generated such that the leading edge of the upstream spot is in the calm region of the downstream spot, the celerity of the upstream spot is decreased and the spots ultimately merge. The applicability of the combined bulk convection and gradient transport hypothesis for modeling turbulent diffusion was investigated [6C]. Improvement over previous models could be achieved with the new formulation of turbulent diffusion. The effects of heat release were studied in a planer, gaseous reacting mixing layer formed between two subsonic free-streams, one containing hydrogen and the other containing fluorine [30C]. The overall entrainment into the layer was substantially reduced by heat release. The three components of the average temperature dissipation were measured using a pair of parallel cold wires in an approximately self-preserving turbulent boundary layer [39C]. The time scale for the turbulent-energy dissipation was found to be approximately equal to that for the temperature dissipation. A previously-published eddy viscosity model was applied to the analysis of the conditions in the near-wall region of a pipe flow [67C]. The dimensionless pitch of the horseshoe eddies on the wall in the developed flow was obtained. A surface-renewal calculation of thermal coupling between a thick solid and a well-mixed, low-Prandtl-number fluid, was applied to the calculation of the temperature variance near the wall [68C]. The results are for numerical solutions of the turbulent variance transport equation. The wake region of a turbulent boundary layer was shown to exhibit simple exponential behavior at elevated levels of free-stream turbulence [66C]. Analytical expressions were provided for the Reynolds shear stress and the turbulent heat transport term. A new proposal for closing the energy equation was presented at the two-equation level of turbulence modeling [54C]. The eddy diffusivity for heat was given as a function of the temperature variance. Spectra of all three velocity fluctuations and of the temperature fluctuations were obtained in the self-preserving region of the turbulent wake behind a circular cylinder [5C]. The preferential transport of heat by small scales is maintained, if not enhanced, within the turbulent zones.

Heat transfer effects of an isolated longitudinal vortex embedded in a turbulent boundary layer were examined experimentally [20C]. The local increase in Stanton number was attributed to a thinning of the boundary layer on the downwash side of the vortex. Adiabatic disturbances that occur in an inviscid compressible fluid rotating as an unbounded Rankine vortex were considered [70C]. Cases were presented in which the vortex was confined in a cylinder. An experimental investigation was made of the three-dimensional boundary layer that results when a Rankine-like vortex is bounded by a fixed plane boundary coaxial with the axis of rotation of the vortex [59C]. In spite of the high three-dimensionality of the layer, the tangential component of velocity conforms to the same law-of-the-wall as its streamwise counterpart in two-dimensional turbulent boundary layers.

A solution was presented for temperature distributions of a stretching sheet cooling down in a non-Newtonian fluid obeying Walter's liquid B model [19C]. A turbulent viscosity model was proposed which takes into account the effect of temperature inhomogeneity on friction and heat transfer in a turbulent boundary layer [18C]. A considerable effect of the temperature factor on the value of friction coefficient and heat transfer under pronounced non-isothermal conditions was demonstrated.

Experimental results were presented showing the response of the heat transfer coefficient at the base of an open-ended cylindrical cavity to yawed impingement of the free-stream flow on the cavity opening [71C]. When the free-stream flow was yawed, the heat transfer coefficient rebounded from its low non-yawed values. The enhancement of mass transfer by vortices induced in a cavity due to external channel flow was numerically evaluated [8C]. A comparison with experimental data for an aspect ratio of one was made. Experiments were performed to determine the local response of heat transfer on the outer surface of a longitudinal cylinder to differences in flow pattern [34C]. Configuration-dependent correlations were achieved both for the maximum Nusselt number along the outer surface and for the Nusselt numbers in the downstream region. Heat transfer in turbulent boundary layer reattachment behind two-dimensional barriers on a plane surface was measured [60C]. The existence of two trends, depending on the barrier height, was shown. A combined analytical–numerical approach was presented for examining the turbulent boundary layer flow and corresponding skin friction and convection heat loss as functions of free-stream velocity and angle of attack [76C]. Heat transfer from a cylinder to a Newtonian fluid in laminar flow was solved using the finite-element method for low to intermediate Reynolds numbers [9C]. Calculations, presented for a range of Prandtl numbers, were used to develop a new correlation. Experiments were made to compare with the calculated results [10C]. A temperature-sensitive hot wire under constant-temperature operation was analyzed to predict its frequency response to temperature fluctuation [48C]. Some attenuation in the gain sometimes appears in the range of energy-containing eddies. The results of calculations of heat flux on three-dimensional bodies given the pressure distribution were discussed for bodies of different shape [88C]. On the front surface, the three-dimensionality of the flow in the boundary layer does not have much effect, the controlling factor is the dependence of the heat flux on the local pressure. The two-dimensional Navier–Stokes equations and the energy equation governing steady laminar incompressible flow were solved by a penalty finite-element model for flow across finite depth, five-row deep, staggered bundles of cylinders [17C]. Results were compared with available experimental data. Equations which govern laminar flow past a sphere with surface mass transfer were solved numerically for low Reynolds numbers [11C]. Results included wake lengths, angles of separation, drag coefficients and average Sherwood numbers. A study was made of the effect of axial heat conduction on the unsteady, incompressible, laminar, forced convection heat transfer of liquid metals along an isothermal circular cylinder in longitudinal flow when the free-stream velocity varied arbitrarily with time [73C]. Experiments were performed to measure the heat transfer characteristics of spiral pipe flows [85C]. Three types of flows were identified: passing, circumferential and mixed, depending on the pitch-to-diameter ratio. Results were presented of a study into the optimum way of enhancing forced convection heat transfer using turbulence promoters [74C]. It was shown that a possible reason for the fact that turbulence promoters do not show much improvement in performance may be due to the considerable reduction of the local heat transfer rate around the region where the separated flow reattaches. Conjugate heat transfer results for two-dimensional, developing flow over an array of rectangular blocks, representing finite heat sources on parallel plates, were presented [15C]. Heat transfer characteristics resulting from recirculation zones around the blocks were presented.

A formulation for the analysis of forced convection heat transfer from both a concentrated thermal source and a uniformly distributed thermal source was presented [47C]. A non-similar boundary layer energy equation was obtained by introducing a parameter for relative source strength and a dimensionless temperature based on the two characteristic temperatures of the sources. Experimental results for a turbulent boundary layer on a permeable surface with helium injection at an angle of 90° were discussed [33C]. When the pressure gradient becomes zero, the fluctuational components of the longitudinal velocity become much higher than in a boundary layer of constant density.

The effective diffusion coefficient of a passive component was derived for motion in periodic, two-dimensional, incompressible convective flow in the presence of an intrinsic local diffusivity [63C]. The diffusivity is readily calculated for small values of the asymptotic diffusivity; but, for arbitrary values, solution requires numerical methods. The influence of non-uniform surface temperature distribution on laminar boundary layer stability was discussed [41C]. It is shown that by an appropriate selection of surface temperature distribution, it is possible to obtain larger runs of laminar flow. This is important from the point of view of boundary layer control, including laminarization. The unsteady, laminar, incompressible, second-order boundary layer flow at the stagnation point of a three-dimensional body has been studied for both nodal and saddle point regions [40C]. The parameter characterizing the unsteadiness in the velocity of the free-stream, the nature of the stagnation point, the mass transfer and the Prandtl number were shown to be important characterizing parameters for the skin friction and heat transfer evaluation.

Boundary layer transition on convex curved surfaces was experimentally investigated [83C]. The curvature effect was shown to be important when the free-stream turbulence was low; but, when the disturbance level was high, its effect dominates the curvature effect. Thermal instability of forced convection flow over an isothermal, horizontal, flat plate, in the form of longitudinal vortices, was examined by introducing three-dimensional spatial dependence of the perturbation quantities to the analysis [87C]. The effect of streamwise varying temperature perturbation was shown to stabilize the flow, as compared with the isothermal case. The development of a temperature field in a turbulent flow with unsteady heat transfer was discussed [58C]. Experimental results for a flow with a sudden change in heat release at the channel wall were presented. Thermally stratified unsteady flow caused by two-dimensional surface discharge of warm water into a rectangular reservoir was investigated [42C]. The warm layer penetrates more rapidly into the cold layer at smaller Richardson numbers because of decreased instability. The unsteady streamwise pseudo-vortical motion model was used in a numerical analysis of turbulent heat transfer near the wall [35C]. The predicted turbulent heat flux and turbulent Prandtl number are dependent upon the Prandtl number under the strong influence of the prescribed wall boundary condition. An analysis was presented for the linear non-parallel wave instability of boundary layer flows [44C]. The neutral stability curve was defined by letting the maximum growing rate of the disturbance intensity be zero. Agreement was found with experimental data. Heat transfer coefficients to helical coils in agitated vessels were investigated [28C]. Reynolds number was found suitable for the correlation of the experimental data. The onset of instability in mixed convection flow adjacent to an isothermally heated, inclined plate was determined through flow visualization [1C]. A critical Grashof–Reynolds number relationship for the onset of instability was presented.

An analytical investigation was presented for the effects of unsteadiness, suction and internal heat generation on the continuous flat surface problem. Results were given for the mean flow component [78C] and for the oscillatory flow component [79C]. Results of an analytical and numerical study of natural convection in a rectangular porous layer subjected to uniform heat fluxes along its vertical boundaries were presented [81C]. The boundary effects are more pronounced in high-porosity media where the flow rate and heat transfer are significantly reduced.

A relationship was found between temperature and turbulence intensities and mean flow characteristics, while also examining the role of compressibility in turbulent motion [23C]. This addresses the issue of

Reynolds' analogy in supersonic flow. An approximate method was presented for calculating the heating rates on three-dimensional vehicles such as the Space Orbiter [26C]. Heating calculations can be made with this method along a typical streamline. Algorithms for the determination of the coefficient of heat transfer and recovery temperature of a gas flow by way of the calorimeter method were presented [24C]. The joint effect of the longitudinal pressure gradient, non-isothermicity and compressibility on the processes of heat transfer and friction in a boundary layer was studied [38C]. Applications to nozzle flows were discussed. A series solution of the full Navier–Stokes equations with slip and temperature jump surface conditions in hypersonic flow around a sphere was presented [32C]. Results predict a flow structure in the outer part of the layer which is significantly different from that given by the direct simulation Monte Carlo (DSMC) method. Results of an experimental study of flow over an axisymmetric cone with isentropic compression were reported [7C]. The transverse distribution of Stanton number at the downstream end of the isentropic compression surface is periodic both in the laminar and turbulent flow. A comparison of computed and experimental surface pressure and heating on cones was presented [84C]. A three-dimensional Euler flow field solution was coupled with an axisymmetric analogue technique to determine surface heating. The results of an experimental study of flow over yawed, blunt cones was presented [31C]. Such flows may be accompanied by formation of two points of longitudinal inflection of the bow compression shock, subdivision of the principal heat flux peak on the lee side into two branches, and the appearance of an additional heat flux peak. Numerical results were presented for low-density hypersonic flow about cylindrically blunt wedges [12C]. Translational, thermodynamic and chemical non-equilibrium effects were considered in the numerical simulation by utilizing the DSMC method. A numerical code was developed to predict the aerothermodynamic environment of a highly-swept wing leading edge at zero angle of attack, including the region outboard of the shock–shock intersection [3C]. Real gas and perfect gas models for the thermodynamic properties were applied. A finite-element technique and modeling approach for thermostructural analysis with a reusable surface insulation-type thermal protection system was presented [75]. The approach was shown to be applicable to the analysis of large sections of the shuttle wing configurations. Thermal-control requirements of design-optimized aeromaneuvering performance were presented for space-based application and low Earth orbit sorties involving large, multiple plane-inclination changes [51C]. Recommendations were given for future design refinements. A high-power carbon dioxide laser with a fast axial flow was investigated experimentally and theoretically [53C]. The active medium was described by assuming a five-temperature model and balancing the quantum densities of vibrational states of the carbon dioxide and nitrogen molecules.

A study was conducted to investigate the mechanism that causes free-stream turbulence to increase heat transfer in the stagnation region of turbine vanes and blades [80C]. Results show that the boundary layer remained laminar in character even in the presence of free-stream turbulence. A buoyancy-extended version of the k–W turbulence model was used to predict two-dimensional turbulent wall jets and plumes directed along adiabatic and isothermal walls [49C]. The characteristics of individual small droplets impinging upon a hot surface were investigated [65C]. Heat transfer effectiveness in a low-temperature range of less than 125°C decreases as droplet impingement frequency increases because of interference between the impinging droplet and the remaining liquid film on a surface.

Experiments were run on convective heat and mass transfer from a horizontal heated cylinder in the downward flow of air–water mist [2C]. Heat transfer augmentation of over 19 times was attained at the forward stagnation point. Forces exerted by the gas jet on the molten layer in laser cutting were investigated theoretically [82C]. Both pressure gradient and frictional forces are of the same importance for the melt ejection. The local coupling between sedimentation and convection was discussed [57C]. The hydrodynamic behavior of suspensions was described by a set of coupled equations for the convective flow pattern and for the sedimentation velocity. Local heat transfer and friction coefficients were measured in a circular tube for suspensions of bentonite, some with polymer additives [50C]. The fluid combining clay and polymer exhibited characteristics typical of visco-elastic solutions, and had a high sensitivity to mechanical degradation. An interpretation of the experimental data on mass transfer with large Schmidt numbers in the presence of polymeric additives, which reduce hydraulic drag in turbulent flow, was presented [37C]. The effect of the additive was incorporated into the attenuation factor of the turbulent transfer coefficient in the viscous sublayer. Boundary layer solutions were presented to investigate the steady flow and heat transfer characteristics from a continuous flat surface moving in a parallel free-stream of micropolar fluid [62C].

Results of a study on convective heat transfer from impinging flames were presented [27C]. A large vortex was visible which originated in the shear layer of the flame. The vortex gave low frequency oscillations in measured instantaneous velocities. A numerical prediction of premixed turbulent combustion in jets using a second-order closure model was presented [16C]. Mixing of hot burned and cool ambient gases and the attendant buoyancy effects were found to be significant physical phenomena in the behavior of such lean, premixed, combusting jets. Turbulent structures of a diffusion flame formed in a flat plate boundary layer have been investigated experimentally [77C].

Statistical properties were obtained, taking into account the effect of the mean density variation. The formulation of non-equilibrium thermodynamics with convective flow under the influence of an external potential field was made from two viewpoints, Lagrangian and Eulerian [64C]. Thermodynamic forces and fluxes were defined and two evolution criteria derived. Thermodiffusional convection in the presence of the Soret effect was considered under conditions of poor heat exchange, when convective patterns with a large aspect ratio are formed beyond the instability threshold [29C]. Long-scale oscillatory instability is found to obey the Schrodinger equation with the amplitude modulated on a longer time scale.

The enhancing effect of external force fields on convection occurring at solid–fluid interfaces was interpreted by means of a stochastic relationship [21C]. Results of an experimental study on heat transfer to water drops released successively from a single nozzle into a medium of a denser silicone oil (confined by a pair of vertically-oriented parallel-plate electrodes) were presented [52C]. The heat transfer efficiency levels off as the field strength exceeds a certain critical level due to coalescence of the drops. Experimental results were presented which show the improvement in external heat transfer coefficient of electrically conductive and non-conductive cylinders in a corona wind with and without forced air circulation [13C]. They suggest that corona wind can improve the heating characteristics of an oven and that similar improvement, though less significant, can be seen even in combination with forced convection.

A simplified model was developed for describing the heat and mass transfer through a gas–liquid interface of a wavy, turbulent falling liquid film [86C]. It assumes that turbulent transport near a gas–liquid or a solid–liquid interface is governed by eddies the length and velocity scales of which can be characterized by bulk turbulence and that, in a region near the interface, the turbulence is damped by viscosity and not surface tension. Heat transfer in, and gas diffusion into, free-falling liquid films on diverging–converging surfaces were analyzed [55C]. The tortuous geometry of such surfaces can enhance the heat transfer and mass transfer rates up to 300%. Mass transfer between a gravity-driven accelerating film and a vertical surface was considered [4C]. A similarity solution of Fage and Falkner for the heat transfer behavior of a laminar momentum boundary layer on an isothermal wedge was shown to be useful for solving the concentration boundary layer problem in the developing liquid film.

Measurements of laminar mixed, forced and free convection air flow adjacent to an upward and a downward facing, isothermal, heated, inclined surface, were reported [61C]. Mixed convection correlations for average Nusselt numbers agreed well with predicted results and data. Mixed convection along vertical cylinders and needles with uniform surface heat flux was investigated for the entire mixed convection regime [43C]. For large values of curvature, and/or Prandtl number, the governing, transformed equations become stiff. The flow in a laterally heated vertical slot was analyzed [14C]. The horizontal boundary layer structure generated by this solution, for the case when the horizontal walls of the slot are perfect insulators, was examined.

FLOW WITH SEPARATED REGIONS

The emphasis in this category is on the separated flow over a cylinder and in tube banks. Flow separation due to cavities and backward-facing steps has also been considered.

Among the studies directed at a cylinder in crossflow, ref. [21D] provided a detailed numerical solution for the prediction of the point of separation for the turbulent boundary layer. The effect of yaw on the forced convection heat transfer to a circular cylinder was investigated [19D]. The convective heat transfer to a circular cylinder can be influenced by the use of shrouds; this was examined in ref. [6D]. Reference [14D] dealt with chemical reaction and mass transfer for a gas crossing a graphite cylinder. The *unsteady* convection over circular cylinders was examined [9D]. Heat transfer for other geometries include rectangular cylinders [8D], a sphere [3D], and two wall-attached circular cylinders [1D].

Separated flow over banks of tubes or rods is the subject of many studies. The heat transfer and flow characteristics of low-finned tube banks was surveyed [17D]. Heat and mass transfer in an infinite rod array was considered [23D]. Reference [10D] dealt with the heat transfer in a flow of subcooled water over an inclined tube bank. The influence of spacers on the heat transfer in a rod bundle was considered in ref. [4D], while the effect of turbulence intensity in tube bundles was investigated in ref. [20D]. Heat transfer to inelastic non-Newtonian fluids across tube banks was compared with that to Newtonian fluids [16D]. An experimental study of flow and heat transfer in yawed tube banks was reported [22D]. The effect of flow obliqueness in an in-line tube bank was considered [2D]. Numerical computations for finned and unfinned tube banks were presented in ref. [7D]. Reference [11D] discussed the analogy between momentum and heat transfer for tube banks with oval-shaped tubes. The influence of adjacent tubes on the heat flux to a tube was considered [12D].

Separated flows also occur in cavities, enclosures, and at backward-facing steps. The heat transfer downstream of a fence was considered [25D]. Reference [15D] presented a correlation for the maximum heat transfer coefficient in a reattachment flow region. The relationship between the points of flow reattachment and maximum heat transfer for regions of flow separations was discussed [18D]. An experimental study [13D] dealt with natural convection in the separated region of a backward-facing step. Heat transfer in the separated zone of a nozzle was considered [24D]. An investigation of the heat transfer in shrouded rectangular cavities was reported [5D].

HEAT TRANSFER IN POROUS MEDIA

Heat transfer in packed beds

Models of thermal conductivity of packed beds without fluid flow were analyzed and compared [127DP]. Measurements of thermal conductivities of packed beds of small spherical particles with three different interstitial gases at various pressures were reported, with derived temperature jump distances and thermal accommodation coefficients [35DP]. The extent to which forced flow oscillations augment heat transfer across a porous layer with no net flow was analyzed [119DP]. Analyses of flow and heat transfer were described for interfaces of porous media with other porous media, with a fluid, and with an impermeable medium [128DP].

New correlations for wall to bed heat transfer were presented [121DP, 139DP]. Experiments were reported for wall heat transfer and thermal conductivity of a packed bed [37DP]. Forced convection in cylindrical packed bed tubes was analyzed incorporating radial porosity variations and inertial effects [14DP]. Fluid to wall heat transfer coefficients and radial bed thermal conductivity were measured for packed beds of catalyst particles as functions of Reynolds number and tube–packing diameter ratio [11DP]. Overall bed to wall heat transfer coefficients were maximized with a tube–packing diameter ratio near 6. The influence of temperature distribution in fixed beds upon gas flow uniformity was determined to be significant with moderate temperature gradients and dominant in high-temperature processes [122DP]. A transfer function approach was demonstrated to be useful to determine thermal diffusivity and heat capacity of a porous medium [7DP], and a technique involving a single experiment was described for determining simultaneously the effective thermal conductivity and the wall heat transfer coefficient of tubular packed beds [138DP]. Experiments performed on a radial flow packed bed reactor suggested that the effective thermal conductivity was independent of radial location within the bed [69DP]. A two-region (bulk and boundary zones) model of temperature distribution with no discontinuity (or wall heat transfer coefficient) at the wall was shown to better interpret measured temperature distributions in packed beds of large particles with low thermal conductivity [34DP]. Distributed models for liquid phase packed bed heat transfer were explored [33DP]. An alternating flow model was proposed for heat and mass dispersion in packed beds and shown to match measured results at least as well as random diffusion models [54DP]. A non-local dispersion theory was developed to model dispersion in porous media under conditions where Fick's law has been found inapplicable since length and time scales of transport exceed the scales of velocity field variations [55DP]. Heat transfer coefficient instabilities in packed beds [110DP] and the influence of perturbations in volumetric heat release rate and fluid flow rate upon the temperature field of packed beds [43DP] were discussed.

Heat and mass transfer were modeled for a packed bed within a finned enclosure, and an experiment was performed to evaluate the bed's thermal conductivity and wall to bed heat transfer coefficient [32DP]. Three regimes, related to the flow resistance through the medium, were identified for forced boundary layer flow along a semi-infinite flat plate embedded in a porous medium [52DP]. The fluid to packing heat transfer was related to flow resistance, using the Kolmogorov scale velocity as the link between flow resistance and friction velocity [56DP]. Local fluid to particle mass transfer coefficients were measured for individual spheres in a packed bed and found to vary substantially from averaged values, especially at low Reynolds numbers [49DP].

Fluidized beds

Flow visualization and time resolved heat transfer coefficient measurements were reported for a pressurized fluidized bed [17DP], and a one-dimensional model of bubble growth was presented based upon experiments performed in beds of large particles [26DP]. Numerical solutions of transient heat transfer to particles touching a heat transfer surface were again shown to greatly overpredict measured fluidized bed heat transfer coefficients, supporting the hypothesis of a gas gap between the affected solids [93DP]. Experiments in a fluidized bed displayed two maxima in the dependence of immersed heat exchanger coefficients upon fluidizing velocity [80DP].

A heat transfer probe for measuring the total and radiative heat transfer coefficients between a gas-fluidized bed and an immersed surface was described and results used to recommend predictive models [73DP]. Experiments and analysis of fluidized bed to wall heat transfer were reported, with attention paid to the contributions of bubbles and emulsion at high temperature [25DP]. Measured radiant transmission through packed and fluidized beds of glass beads exceeded predictions of the two-flux model employing coefficients determined from independent scattering theory [15DP].

Experiments showed significantly different patterns of heat transfer coefficients for an immersed tube close to the distributor as compared with a tube in the bubbling zone [40DP]. Heat transfer between a shallow fluidized bed and an immersed tube was investigated [58DP]. Heat transfer coefficients and pressures were measured around a horizontal cylinder in a fluidized bed, and observations of flow characteristics were reported [64DP]. Experiments were reported for a low pressure drop fluidized bed heat exchanger using low density particles with a single row of cylindrical tubes [60DP] and with a single row of rectangular tubes [59DP, 61DP]. Heat transfer coefficients measured in a pilot scale fluidized bed combustor were compared with existing models and correlations [31DP]. Use of finned heat exchange surfaces in fluidized beds was explored [44DP, 45DP, 57DP, 84DP]. The effects of immersed heat exchanger surfaces on the flow behavior of fluidized beds was examined [38DP, 82DP]. The influence of distributor design [112DP] and of forced bed vibration [71DP] were investigated.

Experiments in a circulating fluidized bed confirmed a proposed cluster renewal model of heat transfer [8DP]. Preliminary heat transfer data were provided from the high temperature operation of a circulating fluidized bed [30DP]. Heat transfer coefficient measurements at two surfaces on the wall of a hot, pilot scale circulating fluid bed were reported [134DP], showing little dependence on gas velocity but substantial dependence on the effective suspension density and axial position.

A model was proposed for heat transfer between a magnetically fluidized bed and a surface [135DP], and a bubbling-bed model was used to explore heat and mass transfer in fluidized beds [21DP].

Combined heat and mass transfer

The present status of the theory of combined heat and moisture transfer in porous media was reviewed [16DP]. Measured drying rates of initially saturated, non-hygroscopic capillary porous bodies were well represented by constant rate and falling rate models [113DP]. Experiments were also reported for the drying of a bed of glass beads using convective heating at one exposed surface [51DP], and for the moisture and heat transport in porous building materials [98DP]. Several models were presented for prediction of heat and moisture transport in unsaturated porous media [4DP, 18DP, 23DP, 94DP, 118DP, 124DP]. Analysis of sublimation of a frozen semi-infinite porous medium was performed yielding an exact solution incorporating both moisture concentration and pressure gradients in the unsaturated region [24DP]. A numerical model was presented for the heat and mass transfer in metal hydride reaction beds [74DP]. Temperature distributions and rates of volatilization were modeled for an oil sand bed subjected to a hot gaseous stream [1DP]. A simple model of high intensity (high temperature and pressure) paper drying was developed and shown to agree well with measured drying rates [103DP]. Microwave heating of soil and of asphalt was modeled and applied to experimental results [27DP].

Natural convection in porous media

A large number of investigations of natural convection in porous media were reported, only a small fraction including experimental efforts. In two-dimensional rectangular enclosures; distributed heat generation with isothermal side walls and cold or adiabatic top and bottom surfaces was analyzed [104DP], bottom surface heating with high Rayleigh numbers was examined numerically and theoretically with a scale analysis suggesting the use of two different temperature scales [126DP], and the horizontal spreading of heat and mass was examined with discussion of the effects of convection and diffusion [137DP]. In inclined, two-dimensional rectangular enclosures; the uniform heat flux in and out of two opposing surfaces was analyzed [117DP, 130DP], as was the case of isothermal boundary conditions on opposing surfaces [83DP]. The response of media composed of vertical slabs with different properties to heating from below was studied [75DP, 91DP]. The natural convection response of a horizontal layer to localized heating from below [105DP] and the behavior of semi-infinite media surrounding hot and cold pipes [39DP] were reported.

Natural convection from vertical plates in porous media was analyzed for cases with non-uniform wall temperature [28DP], for cases where the leading edge of the heating plate is an arbitrary distance above an impermeable horizontal boundary [46DP], and in cases with a non-slip boundary condition imposed at the plate [41DP]. Additionally, the natural convection flow in the buoyant wake above the trailing edge of a heated vertical plate embedded in porous material was analyzed [79DP]. Natural convection from horizontal surfaces in porous media was analyzed for non-uniform surface temperature [86DP] and for a horizontal surface bounded by an impermeable, ambient temperature, vertical wall [47DP]. A transformation was demonstrated by which three-dimensional natural convection near a stagnation point can be reduced to an equivalent two-dimensional problem [100DP]. Solution techniques for arbitrarily shaped two-dimensional bodies producing uniform heat flux [80DP] and non-isothermal two-dimensional or axisymmetric bodies [85DP] were presented.

The effects of thermal stratification of the media upon natural convection from a vertical heated plate [89DP] and from localized heat sources at the bottom of horizontal layers [19DP] were analyzed. Natural convection was also analyzed in porous materials contained in a horizontal annulus geometry [108DP, 116DP]. Experiments with a bottom heated porous layer saturated with water and with temperatures spanning the temperature of water's maximum density were reported [123DP]. Numerical and experimental results were reported for natural convection through an enclosure with a fluid layer and a saturated porous layer side by side [9DP]. The Boussinesq approximation was contested and shown to produce unrealistic results in some natural convection circumstances [97DP].

Mixed convection

Experiments were reported for combined natural and forced convection across a horizontal cylinder in a porous medium [20DP]. Analytical methods were presented for mixed convection over two-dimensional and axisymmetric bodies [87DP] and over curved surfaces of arbitrary shape [88DP]. Mixed convection was analyzed for a vertical cylinder [77DP] and in conjugate heat transfer from a vertical cylindrical fin with lateral mass flux [68DP]. Both aiding and opposing forced flow were analyzed for mixed convection over a sphere [63DP]. Natural convection from vertical porous plates with normal suction was also analyzed [109DP, 120DP].

Instabilities

An approximate analysis presented for stability of natural convection driven by an exothermic reaction in a porous medium was supported by results of a numerical solution of the governing equations [131DP]. Stability in horizontal layers was analyzed under conditions of non-uniform heating [6DP], with bottom heating [53DP], and with the porous layer bounded above and below by thin layers of fluid [99DP]. The transition from steady to oscillatory natural convection was explored for a square, two-dimensional domain [3DP]. Experiments in a finite vertical porous layer with lateral heating, for which a Brinkman model had predicted stable natural convection, demonstrated instability [65DP]. An alternate model, allowing viscosity to vary with temperature, allowed an onset of instability at a Rayleigh number larger than that of the observed onset. Analytical boundaries of stability in vertical porous slabs were evaluated as influenced by a slab width in rectangular, three-dimensional enclosures [12DP] and as influenced by the presence of impermeable, but thermally conductive blocks as the vertical sides of the slab [132DP]. Spatial stability was analytically shown for a class of natural convection flows induced by a heated impermeable vertical wall [136DP]. Stability was explored for natural convection flow adjacent to a vertical boundary for the case where the fluid density exhibits a maximum within the temperature range of the flow field [62DP]. Conditions which induce thermal instabilities in porous media with throughflow were discussed [67DP, 90DP].

Studies of non-Darcy flow

Brinkman models were used to explore natural convection in shallow two-dimensional rectangular cavities [115DP] and in lateral heat transfer through a vertical cavity [66DP]. Experiments were performed in a bottom heated apparatus to explore the effect of Prandtl number [48DP]. Conditions were explored for which the Brinkman term and its wall effect could be neglected in laminar mixed convection flow through an annular porous medium [96DP]. Effects of non-homogeneity of the porous medium were explored for natural convection in a vertical porous layer [76DP], and non-Darcy effects were investigated analytically for natural convection from vertical plates [13DP, 42DP, 50DP], with the last of those cited including experimental results for highly permeable media. Inertial effects, represented by the Forchheimer number, were included in the analysis of natural convection flow within a differentially heated rectangular cavity [106DP]. The combination of inertial, Brinkman, and variable porosity effects was discussed for natural and forced convection [125DP], and was simulated for forced flow in circular and parallel-plate channels [102DP].

Other porous media studies and applications

Forced convection in circular and parallel-plate channels partially filled with porous material was studied [101DP]. A method was outlined for evaluating the friction coefficient and Stanton number for incompressible flows in channels with rough permeable walls [92DP]. A discrete model was presented to represent heat transfer from a given particle to a surrounding bed of particles, with supporting experiments [81DP]. Experiments were described for the evaporation of a binary liquid mixture at the surface of a porous medium [114DP]. Benard and Marangoni effects dominate, respectively, with thick and thin porous layers. Convection from a sphere through a porous spherical shell was examined numerically [72DP]. An expected relationship between temperature and the permeability of gas flow through porous media was experimentally confirmed [107DP]. A theory was presented for the effective thermal conductivity of unsaturated and saturated multiphase media, based on the 'effective continuous media' approximation [95DP]. Forced flow pressure drop and heat flux for an evaporating liquid within a porous medium were discussed [70DP]. Heat transfer coefficients were measured for upflow of three phase gas–liquid–fine particle mixtures in vertical tubes [36DP]. A very large lattice model was proposed to model heat transfer and liquid flow in trickle bed reactors [2DP].

Fixed bed thermal energy storage units were modeled with pebbles [129DP] and phase-change materials [5DP] as storage elements. Measured heat transfer parameters for a porous cooling channel were reported [29DP]. A three-zone model was described for estimating the heat loss through the soil beneath a solar pond [10DP]. Gas–particle heat transfer coefficients were measured in a heated column of spheres at elevated temperatures [22DP]. Exchange of solids between fluidized beds of differing temperatures was explored as a means of gas to gas heat exchange [111DP], and a heterogeneous model for a moving bed reactor demonstrated the possibility of large temperature differences between fluid and solids in a counterflow if the fluid and solid heat capacities (the products of mass fluxes with specific heats) are comparable [133DP].

EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

Thermocouples

A four-year project involving six European laboratories under the auspices of the Community Bureau of Reference of the Commission of the European Communities investigated the calibration of platinum–rhodium/platinum thermocouples, types B, R and S [12E]. A thin-film Pt–Ir thermocouple was developed for monitoring temperatures in semiconductor processing; it exhibited bulklike thermoelectric behavior at temperatures up to 790°C, the highest temperature yet observed for a thin-film pure-element thermocouple [49E]. When a thermocouple is inserted into the center of a glass sphere, the conductivity of the thermocouple leads affects the temperature distribution; a method was described for eliminating this source of error [42E]. Thermocouple errors in a metallic body with internal heat sources were investigated [3E].

Thin-film resistance thermometers and heat flux gages

The theory was discussed for using multi-layered thin-film thermometers to measure transient heat transfer rates, with application to rotating turbine test rigs [15E]. A new method was described for measuring heat transfer rates with multi-layered thin-film gages, with application to wind tunnels [22E, 23E]. An apparatus was described for calibrating circular foil local heat flux gages in convective air flows [6E]. The dynamic response of platinum thin-film thermometers was reviewed [24E]. Measurements of the electrical resistance of electroformed nickel films were reported over the range 4–1373 K [52E]. A new technique was described for maintaining liquid crystal cells at a prescribed temperature, using indium–tin oxide coated glass substrates as both the heat source and the temperature sensor [2E].

Radiative emission–absorption techniques

A flat-plate radiometer consisting of a blackened thin-foil heat-flux sensor mounted on a reflective heat-sink block was described [20E]. The performance of an infra-red fiberoptic radiometer for measurement of low temperatures (i.e. near room temperature) was investigated [54E]. A new metal-film bolometer was developed for measuring the radiant energy flux emitted by a thermal plasma [40E]. Energy transfer mechanisms in optothermal detectors were modeled [31E]. A device was developed for calibrating radiation detectors with fluxes up to 10 MW m^{-2} [28E]. The resolution of television camera tubes for recording thermal radiation was investigated [44E]. Infra-red thermal photography was shown to be useful for the measurement of rapid quenching rates in amorphous alloy formation [14E]. A new reference wavelength method was proposed for use in two-color pyrometry [21E]. The lower precision of spherical radiometers when used in air compared to vacuum was investigated [45E].

Temperature measurements over the range 1300–3500 K in a shock tube were obtained by tuning laser radiation over two OH rotational absorption lines near 306.5 nm [11E]. An infra-red diode laser was used to measure the vibrational temperature of CO behind a shock wave by rapidly scanning two or three adjacent rotational lines from different vibrational transitions; the same experiment included measurement of the translational temperature based on thermal broadening of a single highly-resolved rotational absorption line [7E]. Laser-induced fluorescence was used to measure temperature, turbulent temperature fluctuations and other quantities in a supersonic boundary-layer flow [19E]. A millimeter-size neodymium-glass temperature sensor for measurements in specialized industrial situations was described, based on infra-red fluorescence decay time; the reported accuracy is 2°C in the range -50 to 200°C [18E].

Thermochromic techniques

The dynamic response of a thin film of encapsulated thermochromic liquid crystal was investigated [26E]. The accuracy of the color–phase change paint technique for measurement of heat transfer coefficients was studied [27E].

Property measurement techniques

A cylindrical tricalorimeter for measuring the thermal conductivity of electrolytes was described [38E]. A method was reported for measuring the anisotropic thermal conductivity of oriented polymer films in the direction of macromolecular structure orientation [39E]. The use of transient hot-wire measurements to determine the temperature in solids up to 1300 K was discussed, with correction for radiation between the wire and the specimen [37E]. The photothermal microscope, which utilizes the thermal lens produced by crossed laser beams, can be used to determine the thermal diffusivity of a biological sample [10E]. Although Ångström's method assumes that the length of the sample rod is semi-infinite, it can be applied to measure the thermal diffusivity of solids with short samples if the end remote from the periodic heat source is insulated [33E]. The thermal diffusivity of low-conductivity materials such as ceramics and polymers can be measured using Ångström's modified method [4E]. The use of transient temperature measurements to determine simultaneously the thermal diffusivity and specific heat of a heated sample was refined by including the thermal boundary resistance between the sample and its holder [36E]. A 5 cm^3 automated calorimeter with interchangeable sample vessels for measuring specific heats in the range 10–300 K was reported [50E]. The transfer function of an isothermal flow microcalorimeter was determined to allow measurements under transient conditions [34E].

Cryogenics instrumentation

The properties of several specific silicon diodes for use in low temperature thermometry were reported [48E]. Recent developments in semiconducting temperature sensors were reviewed, along with a description of a fast-response thin-film germanium resistor [43E]. The behavior of carbon-glass resistance thermometers over the range 3.41–20 K and in magnetic fields up to 7 T was studied [25E]. The preparation of carbon composition resistors for cryogenic thermometry was discussed [13E]. It was shown that the heat capacity of thick-film resistance thermometers below 1 K is similar to that of carbon-composition thermometers [35E]. The low-frequency capacitance of various types of glass thermometers was compared in the range 4–100 mK and in a 9 T magnetic field [53E]. A new thermometer was described which is based on the temperature dependence of the negative ion mobility in ^3He [46E].

Miscellaneous

Convexity analysis was discussed as a method for determining heat flux and surface temperature from interior measurements [5E], and a new algorithm was presented for determining thermal boundary conditions based on inverse heat conduction [1E]. A computer algorithm was developed for detecting temperature fronts in a turbulent shear flow based on a spanwise array of temperature sensors [8E]. Quantitative shadowgraphy was described for measuring the temperature distribution in a laser-heated gas [32E]. A transducer was developed for measuring instantaneous local heat transfer rates to surfaces immersed in fluidized beds at combustion temperatures [17E]. The accuracy of a zero-method heat flux sensor was investigated by a simulation using teledeltos paper and current injection through a potentiometer [30E]. A new circuit was developed for measuring transient fluid temperatures using a cold wire as a resistance thermometer [41E], and the effect of cold-wire length on measurements of turbulent temperature fluctuations was studied [9E]. The stability of industrial grade platinum resistance thermometers was investigated over the range 13–273 K [51E]. A method was developed for temperature measurement in a semiconductor junction based on the change in capacitance of the space–charge region due to emission of majority carriers from the trap [47E]. Lateral heat conduction effects on heat flux measurements using the thin-skin technique were studied [29E]. A flexible probe consisting of a thermistor, heat-flow sensor and a heater was developed for continuous monitoring of deep body temperature [16E].

NATURAL CONVECTION—INTERNAL FLOWS

Natural convection in enclosures continues to be of great interest to researchers in engineering, applied mathematics, physics and a number of related sciences including astrophysics, meteorology, and oceanography. Non-linear phenomena, transformation to chaos, applications in manufacturing, and cooling of electronic equipment are all the subject of one or more studies. The investigations will be reviewed through a sequence of categories. The first includes convection in horizontal layers where research on stability, low Rayleigh number laminar flows, high Rayleigh number flows to turbulence, internal energy sources, double diffusive flows, two fluid layers, the influence of surface free energy and several special systems are of interest. Beyond this we shall review convection in inclined layers, in vertical slots, and in shallow layers of large horizontal extent which are differentially heated, then convection in annuli and porous media, thermosyphon activity, mixed (combined forced and free) convection and some special applications of buoyancy driven flows.

New insights continue to be found in the stability problem of Rayleigh–Benard flow in horizontal layers heated from below. An analysis [64F] of fluids with temperature dependent properties indicated the possibility of subcritical hexagonal cells and supercritical rolls. Supercritical instability was found with time varying boundary conditions in a horizontal layer [131F]. The instability of a fluid layer heated from below was correlated [54F] with entropy production and flow in the layer. A linear stability study for a horizontal layer with free upper surface included the effects of the deformation of the surface [9F]. A dipolar fluid was found [112F] to stabilize a layer heated from below. A linear stability study of an Oldroyd B fluid with different thermal and stress boundary conditions indicated errors in earlier studies [65F]. A layer of nematic liquid crystal heated from below was analyzed to show the onset of instability [7F]. The critical Rayleigh number for convection in a porous layer above melting permafrost with nonlinear boundary conditions was found [36F]. A modest flow was found to have a significant effect on Rayleigh–Benard instabilities [50F]. With a vertical flow through a horizontal layer there is a significant decrease in the critical Rayleigh number when the Prandtl number is far from unity [90F].

Other studies considered low and moderate Rayleigh number convection in a horizontal layer heated from below. A two-dimensional analysis [95F] of laminar flow in a gas included the effects of variable properties on the critical Rayleigh number and the Nusselt number. Measurements [126F] indicated the influence of roll size on heat transfer at low Rayleigh number. The influence of aspect ratio on the variation of Nusselt number with Rayleigh number at low Prandtl number was studied experimentally using liquid helium [37F]. Roll transitions were measured [70F] in a horizontal layer as the Rayleigh number was increased and also as it was decreased. A sequence of bifurcations in a layer heated from below was analyzed [132F]. In a horizontal layer roll cell patterns were more stable in an annulus than in a square cell and can exist up to very high Rayleigh numbers [55F]. Two different stationary convection regimes were found in measurements [20F] in a mercury layer slightly above critical. A finite-element technique was used to predict the three-dimensional laminar flow in a rectangular enclosure [96F]. A superimposed horizontal flow significantly changes the roll diameter [97F]. Numerical solution for convection in small to moderate aspect ratio horizontal layers included conditions up to time dependent flow [59F].

A study [74F] of the influence of boundary conditions on the critical Rayleigh number included the influence of several layers of fluid stacked one on top of another. A simplified method predicted the instability of a number of stacked horizontal layers [47F].

Studies on convection at high Rayleigh numbers continue to yield new insights. A boundary layer model was used to predict convection in finite aspect ratio layers [56F]. The existence of 'attractors' in Rayleigh–Benard flow was shown [35F]. A numerical solution for a compressible fluid in a layer heated from below has application to flow in planetary and stellar atmospheres [43F]. The Nusselt number was determined in a horizontal layer heated from below up to a Rayleigh number of about 10^{11} using low temperature helium gas [73F]. Speckle measurements were used [83F] to study convection in a rectangular layer cooled from above to simulate single crystal growth. Analysis of light scattering in a convective fluid indicated the interaction between strange attractors and turbulence [103F]. Real time holography was used to study transient flow in a horizontal layer cooled on its top and bottom surfaces [58F]. Fluctuations in a horizontal layer heated internally and from below were related to the intermittent release of plumes from the upper and lower surfaces [60F].

In double diffusive flow the convective motion is caused by two diffusion processes generally due to gradients in concentration and temperature. The combined heat and mass transfer interrelate to cause a complex buoyancy driven flow. The stability of convection in a circular cylinder was studied using an eigenfunction expansion to determine the onset of steady double diffusive convection [40F]. Calculations for double diffusive convection in a finite rectangular cavity showed bifurcation [5F]. An analysis of the salt fingers produced in overlapping layers with different concentration and temperature including steady-state solutions in two and three dimensions were studied [48F]. A prediction [34F] of the transient growth of a thermal layer in a stable salinity gradient indicated a layered structure. Flow visualization showed the influence of external convection on double diffusive flows in a salt-stratified system heated from below [10F]. The importance of transport processes in crystal growth were studied [127F] in a double diffusive flow with differential heating and concentration gradients both aiding and opposing the thermal gradient. Visualization indicated the growth of the flow regime with heat transfer from a horizontal strip to a stably stratified solution [11F]. With double diffusive convection in a fluid with a maximum density (at a given temperature) an analysis was performed [4F] for different layer boundary conditions.

An important phenomena relates the convection in layers which are driven by differences in surface free energy or thermocapillary forces. Such convection occurs when there is a free surface often in conjunction with a buoyancy driven flow. A thermocapillary driven flow is often called Marangoni convection; when combined with a body force (usually gravity), Benard–Marangoni convection. The relative importance of these driving forces depends on a number of factors including the surface free energy variation, the density ratio, temperature gradient, the layer thickness, and the magnitude of the gravitational or other body forces. An experiment was designed to study thermocapillary flows under reduced gravity conditions [57F]. A hexagonal pattern was found [16F] to be the most stable planform for Benard–Marangoni convection with small layer depth. Experiments on thermocapillary flows with time varying heat flux on the upper free surface of a horizontal layer were performed [63F]. A theoretical and experimental study of the influence of container size and shape on Benard–Marangoni flows shows that in a hexagonal vessel there is minimum disorder with hexagonal cells [17F]. Laser-Doppler velocimetry was used to study the convection in a differentially heated layer including the relative importance of capillary and gravitational effects [123F]. A numerical analysis [67F] was used to predict the critical Marangoni number and wave numbers with internal energy sources in a fluid layer. Thermocapillary flows in the annulus between eccentric circular cylinders were examined [31F]. The onset of flow for combined buoyancy and thermocapillary effects was studied for a layer with a poorly conducting bottom wall [39F]. A linear stability analysis predicted the onset of flow in Marangoni convection with radiation effects in an absorbing fluid [8F]. The influence of buoyancy and capillary forces on convection within two immiscible fluids in a horizontal annulus was studied over a range of Rayleigh numbers [98F]. Convection in overlaying air and water layers was studied including capillary effects [42F]. Unsteady thermocapillary-driven motion in a horizontal layer was studied following a pulse of ultraviolet radiation from a ruby laser [2F]. Oscillatory Marangoni–Benard interfacial instability as it might affect crystal growth was predicted under microgravity conditions for an open layer [38F]. The stability of a two layer system was calculated including both buoyancy and capillary effects [41F].

A number of studies considered convection within irregularly shaped enclosures. A general treatment was developed for the numerical analysis of flows in such geometries [23F]. For two-dimensional flow of convection in a semielliptic cavity a large central cell and two smaller cells near the corners of the cavity were indicated [28F]. Experiments on differential heating in a trapezoidal layer indicated the heat transfer can be estimated from results for rectangular enclosures [61F].

Many studies examined the influence of thermal gradients in the horizontal as well as the vertical direction and also the influence of electric, magnetic or rotational forces as well as gravitational forces. Several studies considered horizontal layers partially heated on the bottom and also cooled on a side as well as the top. In a rectangular enclosure heated from below and cooled on one side, a maximum Nusselt number was found when the heated portion of the bottom surface was somewhat less than one-half the total [91F]. The Nusselt number was determined in a mercury filled plenum [12F] with a heated top and one wall cooled. A numerical solution for two-dimensional convection in a cylinder with different aspect ratios was modeled to study crystal growth [32F]. Convection of liquid lithium in the presence of a magnetic field was studied for the design of a tritium breeding blanket [85F]. Numerical calculations [94F] indicated the Nusselt number for molten silicon in a differentially heated square container in the presence of a magnetic field. Convective flows in a ferro fluid were studied in the presence of an electromagnetic field [106F]. A numerical study showed the influence of combined electrorotational and magnetic fields on convection in a cylinder of conducting fluids [124F].

In a slightly inclined layer the lateral walls can change the orientation of the rolls [79F]. In a long inclined layer separation of two constituents of a binary mixture can be strongly influenced by the buoyancy driven convection [45F].

Several studies considered convective flows in a vertical channel for different boundary conditions and ranges of flow parameters. Results from a boundary layer approximation of convection in a differentially heated vertical slot showed the criteria for development of multiple rolls [24F]. A simplified parametric representation is useful for indicating convection parameters in a differentially heated vertical channel [71F]. Conduction in the walls of a vertical channel can decrease the overall heat transfer and yet increase the strength of the fluid motion [78F]. The influence of radiation absorption and emission on convection of a semitransparent fluid in a vertical enclosure was examined experimentally and analytically [128F]. The interaction between surface radiation and convection in a vertical layer was studied to simulate heat transfer through windows [121F]. Different stable modes were found from numerical investigation of convection in a vertical layer with peristaltically moving walls [72F]. A numerical solution indicated the influence of combined surface heat and mass flux through a vertical sidewall on convection in a slot [119F]. Eddy viscosity and a k–ε model were used to predict turbulent convection in a differentially heated vertical cavity [117F]. Analysis provided streamlines and temperature contours for low Rayleigh number convection in water near its maximum density point [87F]. Multicellular flow was found for convection in a square enclosure containing water near its density maximum [75F].

Analysis for a differentially heated square cavity indicated the potential of oscillatory convection [129F]. Convection within a rectangular enclosure with different temperatures on the boundary walls was modeled to indicate processes involved in crystal growth [19F]. Temperature and velocity profiles were measured in a differentially heated rectangular cavity [15F]. Different flow regimes were observed in a differentially heated cavity containing a low Prandtl number fluid [68F]. Unsteady convection in a rectangular cavity was studied in the transient from a steady flow to a uniform state without flow [122F].

A cubic spline method was applied to study a transiently heated rectangular layer at high Rayleigh numbers [100F]. A propagating temperature field following sudden heating in a vertical cylinder was analyzed using a finite-difference numerical solution of the Navier–Stokes equations [52F]. In a cavity with a vertical wall which is partially heated, a minimum Nusselt number was found following a step change in the wall boundary condition [66F].

A number of studies considered convection in vertical channels with a non-rectangular cross-section. A study on convection in a uniformly heated vertical annulus indicated good agreement of the numerical predictions with measurements of the temperature and velocity fields [3F]. In a vertical annulus containing water near its density maximum, the radius ratio played an important role in determining the nature of the flow regime [76F]. Bimodal convection was predicted for a high Prandtl number flow in a vertical cylinder [14F]. Transient convection in a vertical cylindrical container following application of a differential thermal gradient was studied [27F].

Some studies considered convection in a shallow cavity which was differentially heated through a horizontal temperature gradient. A numerical solution for such a flow indicated a transverse roll structure with low Prandtl number fluids [29F]. Another study indicated the Prandtl number below which the core flow in such a cavity was not parallel to the horizontal boundaries [25F]. The local horizontal temperature gradient to change the heat transport in such a system from conduction to boundary layer flow was predicted [33F]. The effect of variable properties on convection in a shallow differentially heated layer was predicted for a Newtonian fluid [81F] and for flow in porous media [82F]. There is considerable influence of thermal interaction between two layers of immiscible fluids enclosed in a rectangular enclosure which is differentially heated [62F].

In a differentially heated vertical enclosure protruding fins or baffles can have a significant influence on the flow and heat transfer. A numerical study [133F] showed the separated region in a cavity with two baffles is a function of the thermal conductivity of the baffles. A vertical partition in a rectangular enclosure was considered for application to heat transfer in buildings [118F]. The influence of partially conducting horizontal walls and simulated plate fins was considered when predicting heat transfer over a range of parameters [92F]. The influence of corrugated horizontal partitions was considered using a numerical analysis [86F].

In a binary mixture enclosed in a differentially heated vertical layer, the influence of thermal diffusion on the convective regime was examined [110F]. The stability of a binary mixture in a vertical layer was considered with combined effects of heat and mass diffusion [30F].

The velocity pattern was measured for two-dimensional transient convection in a horizontal circular cylinder [107F]. The laminar flow and heat transfer in a circular pipe with a sinusoidal variation of wall temperature was measured over a range of frequencies [101F]. Convection cooling of a round superconductor immersed in a cylinder of liquid helium was determined analytically and numerically [102F]. Experimental and analytical studies of convection in a horizontal cylinder were performed with energy sources within the fluid [84F]. Stratification occurred following transient convection in a cylindrical enclosure [93F].

Good agreement was found between perturbation analysis and a finite-difference technique for convection in a non-uniformly heated annular layer [99F]. Two-dimensional laminar convection in a stratified fluid in an annulus was considered [105F]. The early phase of transient convection in the annulus between horizontal cylinders was calculated from matched asymptotic expansions [104F]. An analysis of low Rayleigh number convection in the space between two concentric spheres shows how the heat transfer between the spheres decreases as the radius ratio decreases when convection is suppressed but then increases when conduction predominates as the ratio approaches unity [115F]. Experiments on convection in a complex enclosure agree well with numerical analysis [111F]. The three-dimensional convection in a region between a vertical square rod and a surrounding vertical cylinder was analyzed using a numerical technique [44F]. A numerical model developed for convection in a bed of porous material was used to simulate convection in piles of grain [89F].

Mixed or combined convection is said to occur when the flow is due to both external pressure forces (forced convection) and buoyancy forces (natural convection). Mixed convection occurs in a large number of systems. One sometimes uses the terminology opposing convection when the forces are in the opposite direction to each other and aiding convection when they are in the same direction. Experimental studies on the flow in a vertical duct with opposed mixed convection indicates flow bifurcation can lead to enhanced heat transfer [114F]. For fully-developed flow in a vertically heated tube laminar flow often results in a double spiral [130F]. The influence of thermal boundary conditions on mixed convection in a vertical channel can be significant [6F]. The k–ε model was applied to upward flow (aided flow) and laminarization was found under some conditions [116F]. For opposed mixed convection in vertical ducts a correlation was obtained for the Nusselt number [113F]. Finite-difference calculations indicate complex flow regimes in a vertical layer which has undulating boundaries [125F]. Flow patterns were examined for mixed convection in a vertical cylindrical annulus [46F].

Mixed convection also occurs in horizontal tubes and ducts. In such a channel fully-developed flows were found to depend strongly on the relative conductivities of the wall and fluid [51F]. Another calculation indicated the steady-state flow in a horizontal rectangular duct from entrance conditions to fully-developed flow [77F]. Experiments on mixed convection for low Reynolds number flow found laminar and turbulent flow can co-exist in different regions of a concentric annulus [21F]. The thermal entry region in a parallel channel was examined experimentally [80F].

Mixed convection in enclosures with small inlet and outlets was studied to simulate the heat transfer in buildings [88F]. Convection in a high Prandtl number fluid contained in an oscillating heated tank simulates flows in a rolling ship in a heavy sea [1F]. A horizontal layer with buoyancy and flow due to wind shear was studied for the transient when the shear was applied suddenly [109F].

A three-dimensional numerical analysis of convection in a toroidal loop indicates potential axial flow reversal and secondary motions which are dependent on the Grashof number and the thermal boundary conditions [69F]. Instabilities can occur in a double diffusive thermosyphon and there is a possibility of two convective solutions, only one of which is stable [134F].

Interesting applications of natural convection studies includes flows in a laser melted pool where capillary effects are found to be important when analyzing spot welding [18F]. Temperature and velocity profiles were predicted in a ladle holding molten steel [53F]. Three-dimensional flows of molten glass were studied to aid the understanding of glass manufacturing [120F]. Steady laminar natural convection in a vertical cylindrical enclosure was analyzed to simulate flow in an oil storage tank heated by the sun [49F]. A central receiver for a solar energy system was studied utilizing a cryogenic system to obtain high Rayleigh numbers and separate convective transport from radiation [22F]. A numerical solution was developed to optimize placement of insulation around a thermal-energy storage tank [108F]. Analysis of convection in canned liquids includes transients used in food processing [26F]. Time-dependent natural convection in an exothermically reacting fluid in a vertical channel shows a thermally stratified core develops which moves slowly upward [13F].

NATURAL CONVECTION EXTERNAL SURFACES

Theoretical studies of natural convection heat transfer on a vertical surface continue to be performed. A numerical study shows how trailing edge effects on a vertical flat plate can cause deviation of the plate Nusselt number from the classical boundary layer solutions [59FF]. Laminar natural convection flows adjacent to a vertical surface in viscous oils were analyzed [16FF]. Similarity solutions were found to exist for natural convection from a vertical plate in viscous oil. It is shown that for a heated wall the constant viscosity results underestimate the Nusselt number and overestimate the drag coefficient. For a cooled wall the opposite is true [17FF]. A numerical solution of natural convection heat transfer between a permeable vertical wall with blowing or suction and a power law fluid was obtained which shows that the inclusion of inertia terms is more important for low to moderate Prandtl number fluids than polymeric liquids with large Prandtl number [55FF]. A similarity solution was found for an isothermal vertical wall immersed in a thermally stratified medium. The solution was found to reduce to the classical isothermal plate solution in a uniform temperature environment [24FF]. Experiments were performed on transient natural convection adjacent to a heated vertical plate in the turbulent transition region [18FF]. Numerical results are given for the transient and steady-state velocity and temperature field of water past a vertical flat plate at 4°C [49FF]. Experiments in water and R113 were performed to measure the mean heat transfer coefficient from thin foil heaters mounted on vertical substrates in various configurations to simulate the cooling of microelectronic chips mounted on a circuit board [42FF]. Natural convection from a vertical wavy surface with discontinuous heating was studied experimentally by considering the effect of heat conduction in unheated elements. The wavy surface is constructed with concave and convex semicircular cylinders and has discontinuous heat sources on the concave or convex surfaces [22FF].

Natural convection from horizontal surfaces includes a numerical study of axisymmetric flow and heat transfer above a heated horizontal circular disk which shows the importance of plume and entrainment velocity on the boundary layer of the disk [47FF]. Numerical solutions were obtained for laminar natural convection heat transfer above a heated strip with a heated or unheated obstacle located over the strip [51FF]. The results of an experimental investigation of the vertical temperature and humidity profiles in the thin natural convection water–air boundary layer with small temperature differences between the water and air were made [3FF]. The features of a convective current in a stratified atmosphere generated from a diffused heat source with a specified characteristic horizontal scale was investigated [39FF].

Studies of natural convection heat transfer from a horizontal cylinder include a finite-difference solution obtained for laminar natural convection heat transfer from a horizontal cylinder with constant surface heat flux for a Prandtl number of 0.7 and a Rayleigh number between 10^{-2} and 10^7 [44FF]. A similar study of heat transfer around a uniformly heated circular cylinder was performed up to a Grashof number of 8×10^7 in air [58FF]. Numerical solutions for transient laminar natural convection from an isothermal cylinder for Rayleigh numbers between 10 and 1000, and a Prandtl number of 0.7, show that the results approached previously published steady conditions as the time approaches infinity [4FF]. Experiments were performed which describe the transient development of natural convection from single and two vertically aligned horizontal wires [43FF]. Numerical solutions to the transformed governing equations for laminar natural convection from an isothermal cylinder in a coarse medium under the Darcy approximation were obtained [15FF]. The boundary layer equations were solved for aiding and opposing combined heat and mass transfer by natural convection from a horizontal cylinder [13FF]. An experimental study of double diffusive natural convection from a cylinder submerged in a salt solution was made which shows that the flow conditions depend strongly on the amount of stratification present [38FF].

A theoretical study of laminar natural convection boundary layer flow of a micropolar fluid past a vertical isothermal cylinder was presented in which it is shown that the results for a micropolar fluid exhibit reduced drag and reduced surface heat transfer compared with Newtonian fluids [46FF]. Aiding and opposing mixed convection and radiation to steam in a vertical rod array was studied numerically for triangular and square arrays. Radiation heat transfer was found to comprise as much as 30% of the total when the rods were assumed to be black at a temperature of 2000 K [34FF]. Heat transfer experiments were conducted to investigate the ability to cool a uniformly heated vertical tube by free convection in atmospheric air by using vertical open annuli with adiabatic outer walls. The effects of annulus diameter ratio and heating rates were studied [11FF].

Studies of arrays of vertical surfaces were also made. Steady natural convection cooling of vertical rectangular fins above a horizontal base was investigated when a horizontal adiabatic shroud was positioned adjacent to or above the horizontal fin tips [36FF, 37FF]. A three-dimensional numerical study of flow in a vertical isothermal fin array with a shroud was conducted which covers a variety of geometrical parameters of interest [19FF]. Numerical solutions were obtained for combined natural convection and radiation from a vertical rectangular fin array both with a uniform temperature base plate and a locally heated base plate [52FF]. Experiments were performed on free convective and radiative heat transfer from highly populated pin-fin arrays above a heated base plate [1FF]. Experiments performed in air were used to study the natural convection heat transfer from an array of vertical constant heat flux plates, simulating heated electric circuit boards in a cabinet. Flow blockages near the bottom and top of the array had significant effects on the total heat transfer rate [40FF]. Numerical and experimental studies were made on natural circulation in parallel vertical channels that showed that the circulation direction is a function both of the temperature boundary conditions and the time history of the flow [50FF].

The effect of blowing or suction on the free-convective heat transfer coefficient was extended to a sphere with non-uniform temperature or surface heat flux [14FF]. An electrochemical mass transfer method using $CuSO_4$ was used to measure mass transfer coefficients and perform Schlieren flow visualization for natural convection from cuboids at a Rayleigh number of 10^6 [57FF]. Experiments on natural convection from V-shaped and L-shaped corners were made in air over the Rayleigh number range from 2×10^6 to 1.5×10^9 [48FF]. Rayleigh numbers in excess of 10^{15} were obtained in a rotating-free convection apparatus using liquid helium and a high speed of rotation. Results indicated that secondary flows can reduce the heat transfer by as much as 60% [10FF].

Studies of buoyant plume flows include a study of spacial growth, temperature decay and turbulence structure in axisymmetric buoyant jets. Temperature records obtained with fast response thermistors located in these flows form the basis of the study [41FF]. Experiments in a pressure vessel allowed the measurement of heat transfer on a ceiling above a fire at plume Reynolds numbers of the order of 10^5 [2FF]. Numerical solutions were obtained for the similarity form of the governing equations for an axisymmetric turbulent buoyant plume in a stratified environment. Effects of the stratification were studied and comparisons with existing experimental data made [53FF]. Measurements of buoyant turbulent adiabatic wall plumes along a vertical surface indicated that considerable deficiencies exist in simplified turbulence models when predicting anisotropy, lack of coincidence of velocity maximum and zero Reynolds stress, and variability of turbulent Prandtl/Schmidt numbers [26FF].

Studies of mixed convection on vertical surfaces include an experimental study at high Reynolds and Rayleigh numbers of a vertical flat plate immersed in water. Liquid crystal sheet and hydrogen bubbles were used to visualize the flow. The local Nusselt number decreased by as much as 25% from pure forced or pure natural convection which was caused by suppression of turbulence in the boundary layer [23FF]. Turbulent aiding mixed convection heat transfer on a constant temperature vertical plate was analyzed numerically using boundary layer equations and a modified Van Driest mixing length model over the range of Grashof numbers from 0 to 10^{14}, Reynolds numbers from 0 to 10^7 at a Prandtl number of 0.7 [6FF]. Wave instability of mixed convection flow along an isothermal vertical flat plate was analyzed using a linear theory for fluids with Prandtl numbers of 0.7 and 7. The results show that the two limiting neutral stability curves, one for Blasius flow, the other for pure free convection flow, correspond to two different modes [27FF]. The unsteady mixed convection boundary layer flow of a thermomicropolar fluid over a semi-infinite vertical plate was studied when the free stream velocity varies with time [25FF].

Studies of mixed convection over horizontal surfaces include a study using Squire's method to compute the heat transfer by a mixed convection over a horizontal surface with a constant wall temperature. The theory is applicable to the semi-infinite plate with existence of a laminar boundary layer above the plate surface [32FF]. Boundary layer solutions were obtained for mixed convection crossflow over a fixed heated horizontal plate and a plate moving with respect to the ambient fluid [33FF]. Heat transfer correlations were presented for laminar mixed convection above a moving heated sheet in an otherwise quiescent environment with either constant temperature or constant heat flux thermal boundary conditions [45FF]. An analysis was presented for laminar mixed convection of a uniform free stream flowing along a horizontal adiabatic plate with a line heat source embedded at the leading edge. Both cases of buoyancy assisted and buoyancy opposed plumes were studied [29FF]. The effects of buoyancy induced pressure gradient, Prandtl number, and the ratio of wall velocity to free stream velocity on the laminar forced convective flow and heat and mass transfer over a horizontal plate were studied analytically using a local similarity method [61FF]. A numerical study of the effects of blowing and suction on the laminar buoyancy induced axisymmetric flow over a heated horizontal disk was made [30FF].

Numerical finite-difference solutions were obtained for aiding mixed convection from a vertical, inclined, or horizontal flat isothermal plate. The dependence of the governing dimensionless parameters, Grashof number and Reynolds number, were described for each geometry [60FF]. The effects of viscous dissipation on the stability of a liquid film flowing down a heated inclined plate shows that the viscous dissipation has both stabilizing and destabilizing influences depending on the fluid Prandtl number [12FF].

Studies of mixed convection in horizontal channels include a numerical study to solve the Orr–Sommerfeld problem altered by buoyancy. Two test cases—transition of plane Poisseulle flow affected by stable or unstable stratification and the stability of flow generated by a heater on the lower wall of the channel with and without superimposed flow—were solved [35FF]. An experimental study of the entrance effects [7FF] and fully-developed flow [8FF] were made between horizontal plates. Two entrance lengths were deduced from the velocity profiles, one for onset of buoyancy driven convective instability and one for the full development of the mixed flow. Transverse velocities of the longitudinal roles in fully-developed flow are independent of the forced flow. The effect of geometric parameters on laminar mixed convection in the entrance region of shrouded arrays of heated rectangular blocks was approached numerically for a fluid with a large Prandtl number. The multiple eddies above the block induced by the combined geometric and buoyancy effect lead to a more uniform black wall temperature distribution [9FF].

An analysis of aiding mixed convection was presented for laminar boundary layer flows over vertical slender bodies of revolution with variable surface temperature or heat flux [5FF]. A numerical study of both aiding and opposing mixed convection heat transfer to air inside a vertical tube was made for turbulent flow. The turbulent transport of momentum and heat in a gas of variable physical properties was simulated [54FF]. Acoustic streaming from a speaker was used to enchance the mixed convection heat transfer from a horizontal heated cylinder in a vertical rectangular conduit. It was found that the intermittent aspects of the acoustic streaming were important in the heat transfer enhancement [20FF]. An analysis was made to study laminar aiding mixed convection about a permeable sphere in a micropolar fluid [28FF]. A comprehensive computational–theoretical and experimental study of heat transfer in liquid metal heat exchangers was made for conditions of mixed convection in the inter-pipe space [21FF].

Numerical solutions were obtained for the boundary layer equations for vertical mixed convection flow about a horizontal line heat source over wide ranges of Prandtl number. The aiding flow consists of the evolution between a strong and weak plume and the forced convection. Opposing flow predicts the eventual stagnation accompanied by an unbounded growth of the shear layer [56FF]. New governing parameters for mixed convection wall plumes were determined with new coordinates introduced. The resulting nonsimilar equations were solved using a numerical finite-difference scheme which is valid over the entire range of forced/natural convection [31FF].

CONVECTION FROM ROTATING SURFACES

A variety of systems involving heat transfer in the presence of rotating surfaces were investigated. For a rotating disk chemical vapor deposition reactor the effects of boundary conditions on the flow pattern and the transfer were studied [9G] and a numerical model describing the behavior formulated [8G]. A series of studies focused upon the fluid mechanics and heat transfer characteristics of rotating disks. For a stratified rotating disc flow similarity solutions were presented [11G]: for a disk rotating in a gas the effect of suction on laminar compressive flow and heat transfer close to the disk surface was examined [4G]. In the instance of a disk rotating in the vertical plane the oscillatory free convection of the fluid from the disk surface was considered [6G] and for an enclosed rotating disc the problem of unsteady laminar flow along the surface was attacked [14G]. Two rotating disks separated by a small gap experienced the steady magneto-fluid-dynamic flow of a fluid between their surfaces. A numerical analysis of the problem yielded asymptotic solutions [31G]. In an attempt to enhance the heat transfer from a rotating disk a turbulence promoter in the form of plain ribs (with and without a slit) was used. Local and average heat transfer coefficients were measured using the naphthalene technique [28G]. In a dual parallel co-rotating disk system the fluid flow and heat transfer characteristics were studied experimentally; local heat transfer coefficients along the disk radius were measured and the flow patterns between the discs visualized using a laser-light-sheet method [20G]. For spheres the heat transfer from a vibrating, rotating sphere in an air stream was studied [17G]. For an isothermal rotating sphere in a stream of arbitrary direction with respect to the axis of rotation, power series of several variables were applied to determine the laminar three-dimensional mixed convection flow [18G].

Rotating tubes undergoing heat transfer attracted the attention of investigators for a variety of circumstances. The induced flow in uniformly heated vertical annuli with rotating inner walls was analyzed numerically [7G]. Another study treated buoyancy driven flows in a rotating cylindrical annulus. A spectral (Tau–Chebyshev) method was used to predict the motion of the rotating fluid under the influence of a horizontal temperature gradient [26G]. A follow-on study [23G] treated the transitions to asymmetric and vacillating flow for convection in a rotating cylindrical annulus. Flow in a gas-filled rotating annulus was also analyzed by the finite-element method [2G]. The enhancement of heat transfer on a rotating cylinder by turbulence promoters with a slit parallels the previously cited work on disks [27G]. Reference [32G] gives the measured pressure drops for axial flow through an annulus with a deep-slotted outer cylinder and rotating inner cylinder. Using an analytical and numerical process the unsteady flow of a slightly rarefied radiating gas in a rotating channel was studied with results which apply to vacuum technology, astrophysics and re-entry heat transfer [3G]. Heat transfer with phase change in a rotating channel was considered in two studies. The first considered heat transfer with helium and nitrogen boiling in a channel rotating about an axis parallel to its own axis. The heat transfer coefficient and critical heat flux vary substantially around the tube circumference [1G]. The second measured the effect of rotation on the local pattern of melting and on the overall rates of melting and energy storage in a horizontal tube [10G]. For square-sectioned ducts rotating in the orthogonal mode numerical analysis yielded information on the turbulent momentum and heat transport [12G]. In an experimental study of wall-to-particle heat transfer a small rotary drum heat exchanger was employed with nine different granular materials, the results correlated by a semi-empirical relation incorporating the important variables [19G]. A steam-generating channel in the form of a helical coil of small radius was analyzed in order to determine the temperature distribution [15G].

There are a number of papers where stability considerations are central. Different patterns of fluid flow between the coaxial cylinders were determined due to the imposition of a new mode of stability [22G]. The influence of rotation on inhomogeneous mixing in axisymmetric sudden-expansion flows was reported [29G]. Another study examined the convective motion of a fluid in a rotating annular vessel in the presence of an unstable vertical temperature gradient. Consideration was given to the simultaneous action of two convective instabilities—namely Rayleigh–Benard and lateral. An experiment confirmed the main results forecast by the model [5G]. The third part of an investigation of the stability and heat transfer of rotating cryogens reported the effects of finite cylindrical geometry and rotation at the onset of convection [24G]. For a deep rotating fluid differentially heated from below the onset of spatial oscillations was examined [25G]. A system consisting of a rotating stratified fluid was considered in relation to its reaction to local thermal effects [21G] and with regard to the influence of boundary mixing [13G]. The unsteady laminar, incompressible free convection boundary layer flow in the stagnation region of a rotating sphere was studied. The unsteadiness in the flow field was caused by sphere rotation and the time dependence of the temperature and concentration of fluid at the wall. The skin friction, heat transfer and mass diffusion were influenced by buoyancy, Prandtl number and Schmidt number [30G]. The measurement of velocity and temperature with thermistor anemometers in a thermally stratified rotating fluid was discussed [16G].

COMBINED HEAT AND MASS TRANSFER

Traditionally this section on heat and mass transfer includes a variety of heat transfer situations in which mass is added to a flow. Some of these relate closely to almost pure heat transfer such as film cooling, transpiration cooling and impingement heat transfer from one or more jets striking a surface. Others are more closely related to a net mass transfer process such as ablation and drying systems.

Heat transfer downstream of a film cooling slot was measured at high injection rates [23H]. Lateral injection from a film cooling hole spreads the effectiveness over a significant lateral span of the surface [6H]. Film cooling of a turbine blade with injection through two rows of holes is strongly influenced by the complex flow and vortex pattern near the end-wall of the blade [7H]. Film cooling studies in which the effectiveness and mass transfer were measured in essentially the same apparatus generally agree with earlier results [22H]. Modification of a two-dimensional boundary layer numerical analysis to include three-dimensional effects near injection was used to predict film cooling following injection through a row of holes [18H]. Film cooling of a scramjet model was studied in a free piston shock tunnel [14H].

Predictions were compared with measurements of the heat transfer in the region of a wall jet [24H]. Heat transfer was studied for flow in a convergent channel with angled injection through the walls [1H].

A theoretical analysis was presented [4H] for transpiration cooling of rotating blades with incoming flow through radial channels. Equations for three-dimensional analysis of ablation were studied to develop a method for predicting heat and mass transfer from a surface exposed to a high temperature gas stream [13H].

Local heat transfer was measured on a surface exposed to an array of impinging jets in a crossflow [8H]. The optimum hole density for maximum heat transfer was determined from measurements of heat transfer from an array of impinging jets [2H]. The influence of restraining walls on crossflow and heat transfer with an array of impinging jets was examined [15H]. A related study considered the influence of crossflow on the heat transfer from a ribbed surface [21F]. Another study on the influence of crossflow on heat transfer from an array of jets included a number of experimental measurements [5H]. The heat transfer from a jet impinging in a closed cavity was studied using a mass transfer technique [20H].

A study was performed to optimize the heat transfer from high speed impinging jets on a flat surface [10H]. In a related study the influence of angle of incidence and other parameters was considered in optimizing heat transfer from burner jets to a metal surface in a furnace [11H]. The temperature distribution on a surface of steel can be smoothed out by impingement of a turbulent two-dimensional air jet [9H]. The influence of nozzle spacing and ambient temperature on heat transfer to a row of jets impinging on a cylindrical surface was measured [17H]. A conjugate problem was analyzed for a liquid jet impinging on a semi-infinite solid [19H].

The influence of transverse velocity due to a condensing phase can have an influence on heat transfer similar to that which occurs at a surface with suction [3H]. A diffusion model for moisture was used in an analysis of drying of a bed of grain [16H]. Experiments were conducted on drying of thin layers of maize [12H].

CHANGE OF PHASE—BOILING

Studies of pool boiling and fundamental mechanisms of boiling

The history of developments in boiling heat transfer research was summarized [120J]. Nucleate boiling behavior of various fluids was described [128J]. Bundle effects were presented [29J] for small multi-tube bundles in pool boiling and a predictive model of the tube bundle effect on nucleate boiling at the surface of horizontal tubes in bundles was presented [49J]. Analysis and experiments were described regarding diameter and departure frequency of bubbles from artificial nucleation sites [32J], leading to a mechanistic model [31J] of nucleate boiling on surfaces with prepared sites. A shadow optical technique was used

[178J] to explore the dynamics of temperature fields in flowing subcooled liquids near the onset of boiling. Experiments were reported on the liquid flow field near growing and ascending bubbles [116J], and analytical predictions of heat transfer based on these measured flows agreed well with data. High speed photographic studies [59J] related coalesced bubble evolution with instantaneous heat flux for pool boiling near the point of critical heat flux. Analysis suggested that the macrolayer cannot transfer heat at an adequate rate to support the large heat fluxes near burnout [36J] leading to the development of an alternative macrolayer model.

A holographic apparatus was used [177J] to explore evaporative processes in pure and binary mixture droplets on a flat plate. Modeling of the transient heat transfer to a water droplet on a surface was discussed [93J]. Water droplets superheated on a quartz surface exhibited explosive nucleation after a period of quiescence, supporting a theory of secondary nucleation [58J].

Forced periodic passage of bubbles past a heated portion of a narrow vertical rectangular channel was found to increase measured heat transfer coefficients [101J]. The dynamics of a single growing vapor bubble confined by a closely-spaced unheated surface parallel to its heat source were analyzed [45J]. Three confined flow boiling regimes were identified for crevice boiling using high speed photography and temperature measurements [163J].

Effects of dissolved gas [16J] and of electrical fields [48J, 147J] were also reported.

Enhanced surfaces for boiling

Many studies focused on the use of surfaces with random porosity to enhance boiling. A method for production of and improvements obtained by porous boiling surfaces were described [136J]. Effects of surface orientation and surface enhancements for pool nucleate and film boiling of R11 were measured [66J]. Porous surfaces greatly promoted heat transfer in falling film boiling of R114 over vertical tubes [44J]. Improvements by sintered porous layers on horizontal surface pool boiling of water and methanol were reported [91J]. A brief summary was provided of extensive studies of the effects of porous surfaces on pool boiling of water and water–ethanol mixtures [156J]. A porous polyurethane covering on a tube exhibited reduced incipient boiling heat flux and improved coefficients of heat transfer [87J]. Experiments with the onset of boiling on porous surfaces supported a hypothesis of the importance of the relative sizes and abundance of active pores and of vapor channels within a porous layer [94J]. A bi-modal distribution of pore size was found to provide greater enhancement of heat transfer than a uniform pore size [78J]. Capillary structure effects were explored in modeling bubble activation in non-flooded capillary material [79J]. A one-dimensional model was proposed for porous surface boiling heat transfer behavior [80J].

Pool boiling of water and R113 at atmospheric pressure was investigated on plain, low-finned, and GEWA-T finned surfaces, with the latter displaying strong evidence of enhancement and the existence, for each fluid, of an optimal gap spacing between fins [14J]. Results were also reported for the performance of a special porous surface designed to include tunnels, pores, and ribs beneath the pores to prevent flooding of the tunnels [84J]. Thin layers of loose particles were found to enhance or degrade the energy transport ability of a surface with nucleate boiling depending upon the relative thermal conductivity of the particles and the liquid; no measurable effect of layer thickness or particle size was observed [34J, 155J]. A machined and welded copper matrix exhibited strongly enhanced pool boiling heat transfer in liquid helium [57J].

Larger scale extended surfaces were also explored with analysis of rectangular and pin fins with various boiling regimes [168J] and an investigation of optimal fin height and spacing for pool boiling of R113 [82J].

Flow boiling

Hydraulic resistance and true volumetric void fraction were measured in boiling flow of water in a vertical tube [89J]. Skin friction and heat transfer in vertical bubbly flow were modeled assuming that bubbles influence velocity and temperature profiles near the wall in the same manner as a grid in single phase flow, producing reasonably accurate predictions with data for void fractions as large as 0.3 [96J]. An electrochemical method was used to determine turbulence parameters of a bubbly flow near the wall [154J].

Developed subcooled flow boiling enthalpy and vapor content were related [11J]. An earlier model was extended to include non-uniform distributions of heat flux while predicting void fraction over the length of a subcooled boiling channel [10J], and a new model was proposed for the dynamics of flow regime and volume fraction change in transient flow boiling [146J]. The enthalpy at the onset of significant voidage in up-flow was discussed [18J], and it was shown that, with low pressure and low mass flux conditions, the onset occurred at greater subcooling as inlet velocity was increased [140J]. An acoustic method was developed for detecting the onset of sodium boiling in a breeder reactor core [7J].

An optical pulse/holographic method was used to determine the quality limits of flow regimes of upward flowing water and steam in a pipe and an annulus [23J]. Upward, vertical slug flow was examined experimentally to determine slug length and velocity and liquid layer thickness [157J]. A numerical model of an unsteady steam generating channel was described [54J], and its predictions were found to satisfactorily fit data of dryout and rewetting. A new thermal–hydraulic code for sodium flow in a breeder reactor was described and compared with experimental data [125J].

Flow boiling experiments with water in vertical tubes confirmed the satisfactory predictions of the Chen correlation for convective heat transfer but suggested that the nucleate boiling contribution is overpredicted [6J]. Extensive data for saturated flow boiling in tubes and annuli, vertically and horizontally, were well fit by a simple correlation [56J]. A calculation method was demonstrated for the mean heat transfer coefficient for evaporation of refrigerants in horizontal tubes [153J]. Existing correlations were compared with pre- and post-dryout heat transfer measurements for steam–water flow in a rod bundle [83J]. Experiments were described for evaluating the interfacial heat transfer in annular flow evaporation [41J], and the effects of a wavy wall film of liquid at the entry to superheater tubes of nearly saturated, downward flowing steam were explored experimentally [95J].

Horizontal flow boiling of pure refrigerants R152a and R13B1 and their mixtures was investigated; the Chen correlation was found to fit the pure fluid data well and to fit the mixture data well in cases where nucleate boiling was suppressed [141J]. Circumferential variations in the heat transfer coefficients for mixtures were noted to be opposite of the variations observed for the pure fluid flows. Experiments were reported for boiling of water in horizontal and inclined tubes [46J] and rectangular channels [106J]. Flow regimes in an experimental horizontal steam generating pipe were related to non-uniform and unsteady pipe wall temperatures [15J], and certain operating conditions were recommended to be avoided [142J]. Experiments examined flow characteristics and heat transfer in air–water two-phase flow in helical coils with horizontal axes [170J].

Heat transfer coefficients were measured and flow regimes were observed in a cross-ribbed channel operated in vertical and horizontal orientations [172J]. Nucleate boiling was suppressed in most of the observed flows. Enhancements of up to 80% were obtained in the critical heat flux of subcooled flow boiling of R113 in a tube through the use of staged injection of swirl [39J]. Heat transfer coefficients were measured for water–steam flow in vertical tubes with spiral internal ribs at sub- and supercritical pressures [97J]. Effects of twisted tape swirl inserts upon void fraction and critical heat flux relations were measured [81J].

Reduced flow rate and greater inlet subcooling in a steam generator economizer was observed to produce irregularity in the tube wall temperature [138J]. A model was developed for mixed convection in vertical rod bundles and employed to investigate the onset conditions for mixed convection and for flow recirculation [159J]. Flow instabilities in natural circulation boiling channels were studied: applicability of homogeneous models for prediction of density wave oscillations was considered [51J], and effects of pressure losses were examined [50J]. Differences were experimentally explored between disturbance waves in air–water flow and their counterparts in steam–water flow [115J]. Instabilities associated with vapor blockages of flow were probed in a boiling two-phase system [8J, 9J].

Microbubble emission from a horizontal surface in subcooled flow was examined [61J]. Flow boiling was measured for subcooled heptane along heated rods and across coils [114J], and for subcooled water across a bundle of tubes [90J]. A model was presented for the vapor removal from a horizontal cylinder in crossflow nucleate boiling [77J].

Critical heat flux

Critical heat flux (CHF) experiments were performed in the range of parameters expected to characterize advanced pressurized water reactor cores [113J], and the higher pressures and mass fluxes appear to allow greater heat fluxes than previous correlations would have predicted. Allowable steam generating heat loads on tubes and rod bundles were explored [164J]. A correlation was presented for the limiting vapor qualities in forced convection tube flow, encompassing data for ethanol, R11 and R12, water, and helium [86J]. A model for CHF in dispersed-film boiling was presented and shown to match earlier experimental results for R12 and R318c [173J]. The domain of data for CHF in forced flow through vertical tubes was expanded to larger length–diameter ratios [72J], with measured CHF deviating from predictions of standard correlations at extreme length–diameter ratios. Experiments were described and a modified CHF correlation was proposed for subcooled flow boiling in small diameter (1 mm) tubes in which the void fraction was found to be smaller than previous predictions, providing larger critical fluxes and smaller frictional pressure drop [64J]. A correlation was developed for the limiting dryout steam quality in forced convection in vertical tubes [107J]. The influence of channel geometry upon CHF was shown to be small for high mass fluxes, and related primarily to the fractional extent of the unheated wall surface at lower mass fluxes [99J]. Existing correlations for the flowing quality at which heat transfer coefficients begin to diminish in a uniformly heated vertical tube were shown to underpredict the corresponding quality for a finned tube heated from only one side, as in a steam generator wall tube [139J]. Low heat flux sodium boiling experiments were performed to simulate breeder reactor dryout conditions [174J]. Dryout conditions were observed to evolve into either the slug or annular flow regime. CHF from forced flow boiling of potassium in vertical tubes was measured [108J]. High pressure transition flow boiling of water was produced in a concentric tube counterflow apparatus using flowing liquid sodium as the heat source [47J]. A model was outlined for evaluating the liquid distribution and critical vapor content in annular channels with various distributions of heat transfer

[22J]. A concentric tube, sodium heated evaporator was used to explore the boiling crisis under high heat flux conditions [88J].

CHF on a heated disk subject to the forced convective effects of an impinging jet of saturated liquid was measured and correlated for water and R12 and R113 at various pressures [103J, 105J]. Similar studies were performed with the jet emanating from a parallel surface placed very close to the heated disk, producing a radial outward flow [69J]. The maximum heat flux was improved by 45% when the nozzle's plate was modified to produce a circular dam of small height and with the same radius as the facing heater to restrict the fluid's motion [68J]. Also described were experiments in which an impinging jet augmented the boiling on a circular disk immersed slightly below the free surface of a pool of R113 [102J].

Dryout heat fluxes were measured in volumetrically heated particulate beds in several studies. A mixture of heated and unheated particles was used to experimentally simulate dryout in a debris bed [100J]. Dryout was determined to occur due to a countercurrent flow limitation [62J], effects of pressure and of overlying liquid heights were explored [28J], heat fluxes at which rewetting could occur were found to be much smaller than the dryout heat flux [17J], and fluid flow forced through the medium from below was found to increase the heat flux at dryout [165J].

A physical model was proposed to describe the limiting cases of critical heat transfer with rapid increases of heat flux [131J]. Transient burnout in natural circulation within a vertical channel of liquid helium was explored experimentally and modeled, and a similar model was shown to fit the time delays of burnout for stepwise increases of the heat flux in a pool of helium [130J].

Critical heat fluxes were measured for falling films, with the mechanism suggested to be the dryout of a liquid subfilm beneath the separated flow [112J]. An empirical correlation for CHF on a uniformly heated cylinder in crossflow was developed from experiments which extended the data base to include a wider range of vapor–liquid density ratios [71J]. The effects of sidewall blockage and of immersion depth on pool boiling burnout of horizontal cylinders were measured [43J]. A semi-empirical relation was proposed as a boundary between boiling crises of the first and second kinds [109J]. Experiments with dissolved nitrogen in water showed lower CHFs for subcooled gas-containing water [176J].

Film boiling

A post-dryout heat transfer prediction was proposed which includes the effect of vaporization of droplets in the superheated vapor wall layer [55J]. Soviet works from 1983 and 1984 on post-dryout heat transfer and the wetting of heated surfaces were summarized [137J]. Flow visualization of inverted annular flow boiling of R113 was accomplished with a transparent test section and high speed photography [65J]. A model was developed for inverted annular film boiling [5J]. Limiting vapor quality and post-dryout heat transfer coefficients were reported for upward flow of water in a channel nearly enclosed by four parallel tubes [25J].

Rolled protrusions forming circumferential ribs inside and grooves outside of circular tubes were shown to provide enhancement of both film boiling and condensation [67J]. An analysis was presented of forced flow subcooled liquid film boiling over a horizontal flat plate [169J]. A model, following the concept of a cavitation wake, and a confirming experiment were described for the film boiling wake behind a cylinder in crossflow [73J]. A transformation was shown to permit application of a solution for a vertical flat plate with film boiling in a porous medium to natural convection film boiling around a body of arbitrary shape immersed in a porous medium [117J]. The sensible heat correction for energy transport in the vapor film of laminar film boiling and the liquid film of condensation was shown to vary with the Prandtl number of the fluid [143J]. The motion of the liquid–vapor interface during the forced flow film boiling on a sphere was modeled [126J]. A stable water vapor film on an upward-facing heated aluminum surface at temperatures below the Leidenfrost point and with no net rate of vapor generation was described [3J], and a similar film boiling condition with no net vapor generation was described for superfluid helium [4J].

Subcooled film boiling and the minimum heat flux condition were measured and discussed [122J, 124J], and the minimum heat flux condition of saturated pool boiling was shown to be controlled by surface temperature in experiments showing independence of surface configuration and dimensions [121J]. In other studies, a non-equilibrium thermodynamics approach was used to address the prediction of the minimum film boiling temperature [133J], and the effects of size and end conditions upon the minimum film boiling on horizontal cylinders and plates were explored [152J]. Insulating layers of materials upon a copper surface were found to have little influence on developed film boiling, but substantially increased the temperatures at the minimum heat flux condition [123J]. Temperatures and heat fluxes were measured during the transients following the vapor film collapse at the minimum heat flux in water film boiling on horizontal rods [145J]. A procedure was proposed for correlating results of rewetting of hot surfaces [27J]. Experiments in the 'film-transition boiling' regime were reported [135J] with a hypothesis that significant liquid contact occurs in that regime. Experiments and analysis were directed to the cooling and rewetting of debris beds with variations in permeability [167J]. Quenching experiments performed with a hollow sphere accentuated the circumferential variability in heat transfer coefficients and temperature records that might be reduced but are unlikely to be eliminated in solid sphere quench testing [158J].

Several studies were reported which dealt with the cooling of hot surfaces by liquid droplets in vapor. These included analysis of laminar forced convection along a vertical isothermal plate [162J], experiments with vertical sprays incident upon a horizontal plate [175J] and horizontal sprays incident upon a vertical surface [33J], and cooling of surfaces having high thermal conductivities [40J]. A model was proposed to describe the dynamic and thermal effects of a droplet colliding with a wall heated to a temperature above the Leidenfrost temperature [75J, 76J]. Leidenfrost temperatures were shown to be considerably increased as the porosity of the heating surface was increased in a series of experiments evaporating droplets of methanol on ceramic surfaces [12J]. Statistical analysis of an extensive series of experiments which timed the evaporation of individual droplets was used to support the hypothesis of two transition boiling curves [110J], and numerical solutions were presented for film evaporation of a spherical liquid droplet on a plane surface [118J].

Boiling of mixtures and direct contact, immiscible liquid boiling

A predictive model was proposed for pool boiling of multicomponent mixtures, assuming maximal mass transfer resistance in the liquid boundary layer, and dependent only on single component properties and vapor–liquid equilibrium data [149J]. The effects of mixture composition on the boiling characteristics of methanol–water and butanol–toluol mixtures were found to be reduced with increasing heat flux [148J]. A quantitative description was provided of heat transfer upon evaporation and condensation of binary mixtures [166J]. Pool boiling of refrigerant–oil mixtures exhibited non-uniform circumferential heat transfer coefficients on horizontal tubes [19J] and, in certain cases on fine wires [104J], produced slight enhancement, rather than degradation, relative to pure refrigerant boiling. A dynamic surface effect was shown to increase the number but decrease the size of nucleate bubbles when a surfactant was employed to increase the heat transfer coefficient in a flow boiling apparatus [30J].

Experiments boiling immiscible liquids in a natural circulation loop were reported [127J]. Pressure fluctuations and bubble growth behavior were reported for rising droplets of liquid ether boiling in other immiscible liquids [134J]. Direct contact evaporation of immiscible liquid droplets was analyzed for single drop behavior and experimentally evaluated [161J]. Bubble growth rates were measured for droplets of pure, binary, and ternary mixtures surrounded by an immiscible liquid at the limit of homogeneous nucleation [13J].

Flashing

A method was proposed for evaluating the energy distribution of potential nucleation sites in a superheated liquid [160J], and the activation of boiling was explored in relation with boiling sites [129J]. Experiments explored the kinetics of nucleation of superheated liquid helium [150J]. The propagation of the boiling front of suddenly depressurized pools of superheated liquids was explored experimentally [38J, 92J] and modeled, based, in one work, on wall nucleation theory [171J] and, in another work, on mass transfer controlled bubble growth [132J]. The hydrodynamic stability of a liquid rapidly evaporating at a free surface was analyzed [60] to yield the limits of the surface stability. A discussion of existing models of bubbly flows shows that the postulate of thermal equilibrium is not supported in many cases [52J]. Experiments with the rapid discharge (with flashing) of fluid from a horizontal pipe showed liquid discharge rates in excess of those predicted using an equilibrium flow model [70J]. A proposed non-equilibrium model was shown to predict the flow rate and pressure distribution of critical flows in tubes [42J].

Evaporative heat transfer

Mechanisms of heat transfer in the vicinity of stationary evaporating water surfaces were discussed [26J]. Two steady evaporation models were proposed to estimate evaporation rates from ground spills of volatile and non-volatile liquids [74J]. Transient thermocapillary flow induced by a line (wire) heat source on an evaporating free liquid surface was explored analytically and experimentally [151J]. Fluid instabilities were examined as a polar liquid was evaporated at low pressure and/or with microwave heat addition, the latter being modulated by the effect of the local temperature on the local rate of heating [53J].

Experiments and analysis were focused on evaporation of liquid from a partially filled pan recessed in the floor of a rectangular duct with turbulent air flow [35J]. Flow rate, feed height, and wall superheat effects were explored analytically and experimentally for falling film evaporation on a horizontal tube [37J]. A correlation was proposed for climbing film evaporators [24J]. Local heat and mass transfer coefficients were measured in a falling film apparatus using an infra-red pyrometer to measure the interface temperature [119J]. The kinetics of transient, high-rate evaporation of a condensed phase into a vacuum were modeled for pulsed and for harmonically-imposed heat fluxes [98J]. The effects of three-dimensional roughness on the intense evaporation from a surface were explored by direct statistical modeling [1J].

Heat transfer rates to reactor containment cooling spray droplets were predicted with attention to the drag of a moving droplet growing by condensation [63J]. A numerical model of fuel droplet evaporation was developed and used to explore effects of fuel, drop size, pressure and temperature on diesel engine ignition delay [144J]. Experiments and analysis showed that vaporization of droplets of volatile alcohols miscible with water is accompanied by condensation of water from humid air, enhancing the initial vaporization rate of the alcohol [85J]. Several liquid and vapor transport models were assembled and compared for their influence on prediction of dilute, multicomponent fuel spray droplets [2J]. A model was described for the convective evaporation of non-dilute clusters of drops, including the effects of the extent of penetration of the outer flow into the cluster [20J]; dense clusters of drops were shown to evaporate in a diffusion-governed manner, while dilute clusters evaporated in a convectively-controlled fashion [21J]. An Eulerian approach was demonstrated preferable to a Lagrangian approach to modeling of turbulent evaporating sprays [111J].

CHANGE OF PHASE—CONDENSATION

Studies of film condensation heat transfer include the development of a comprehensive correlation which incorporates the effects of interfacial shear stress, interfacial waviness, and turbulent transport in the condensate film. The usefulness of this correlation was demonstrated for annular film condensation inside tubes [9JJ]. An improved approach to condenser design was developed using film condensation models. Applications to the design of standard shell and tube condensers were demonstrated [45JJ]. Similarity solutions for laminar film condensation in the subcritical region for gravity controlled condensation of pure vapors of water and carbon dioxide on a vertical flat plate were obtained numerically [12JJ]. The heat transfer in turbulent film condensation of flowing vapor on a horizontal flat plate was investigated using the analogy between momentum and heat transfer. A four region model was developed that treats the wavy interface as a stiff, rough wall [47JJ]. A theoretical analysis was made of laminar film condensation heat transfer to a cooled, small downward facing surface [46JJ]. Nusselt's theory of film condensation was used in the processing of results from experiments on gasoline vapor condensation [14JJ].

An analysis was made of one-dimensional vapor condensation through a non-condensable gas layer in a static vapor cavity [32JJ]. Elementary models of film condensation coupling a laminar water film with an air–steam mixture boundary layer under steady-state conditions were compared for some simple physical situations. Two categories of models were tested, those using Rose's closed form solutions, and those making use of the Chilton–Colburn analogy [43JJ]. A theoretical study of laminar forced convection condensation of a binary mixture on a flat plate was given. Similarity solutions for seven kinds of binary mixtures were obtained numerically [11JJ].

A study of droplet condensation of water vapor showed that local time–temperature measurements made on a vertical plate showed a strong correlation to droplet formation and removal [1JJ]. An analysis of steam droplet condensation data showed that the heat transfer measurements cannot be used to determine the condensation heat transfer coefficient directly as the upper limit of the condensation coefficient was found to be 0.93 rather than the 0.6 reported earlier [38JJ]. The roles of pressure drag, friction drag and condensation drag were delineated theoretically for a drop experiencing condensation [23JJ]. Heat transfer characteristics for drop-wise condensation on new surfaces were determined through temperature measurements and the results obtained were compared with drop-wise condensation studies from various sources. Lifetime experiments were conducted on both a copper–chrome surface and a mechanically polished surface which showed a lifetime of over 8500 h [48JJ]. The heat transfer coefficient was measured for drop-wise condensation of steam over a pressure range from 1 atm to 1 kPa using five condensing surfaces. The nucleation site density was not directly related to surface roughness but was affected by physio-chemical conditions of the surface [16JJ]. Fourteen polymer coatings were evaluated to test their ability to promote and sustain drop-wise condensation of steam. Tests on a horizontal tube indicated the steam side heat transfer coefficient can be increased by a factor of 5–8 using a polymer coating [17JJ].

A study of electrical field enhanced condensation heat transfer in the presence of a non-condensable gas was made for R113 and hexane near a vertical plate. With gas concentrations below 10%, a uniform electric field should be applied, at higher concentrations, a corona discharge should be used. A seven-fold increase in heat transfer coefficient was found in corona discharge conditions [3JJ]. Results were also made of heat transfer enhancement of condensation of R113 and hexane in a uniform or pulsed electric field. It was seen that with condensation of pure vapor the greatest heat transfer enhancement was achieved in a constant field while when a non-condensable gas was present the best enhancement was achieved using a pulsed field [4JJ]. It was found that a bubbling condenser operated in a dynamically stable mode and exhibited a high thermal efficiency that was independent of a concentration of non-condensables next to the heat exchanger surface [2JJ].

The local heat transfer coefficient at the lowest part of a horizontal tube was studied by considering the behavior of departing drops. It was found that the local heat transfer coefficient is mainly influenced by the covering effect and the tube diameter [20JJ]. The behavior of a water drop with a constant weight on an unwetted tube was investigated using a video tape recorder. The critical still mass, the falling velocity of the water drop and the condition in dropping from the tube were investigated [21JJ]. The heat transfer coefficient of film condensation on a vertical bank of horizontal tubes was found to decrease as the number of rows increased due to the effect of inundation. However, frequent sweeping of the surface by drops falling from the tubes above are likely to enhance the heat transfer in the case of drop-wise condensation and would exceed the effect of inundation [39JJ]. Heat flux during steam condensation on a horizontal tube bundle was measured for pressures between 0 and 11

MPa which showed a range of heat flux between 4×10^4 and 3×10^5 W m^{-2} [37JJ]. An experimental correlation of Sherwood and Nusselt numbers with Reynolds number was given for a gas flow containing water vapor that flows through a horizontal tube bundle. The numerical correlation can be applied to the mass transfer in a gas flow containing water vapor and the Stefan flow caused by condensation of water vapor greatly increases the convective heat transfer [44JJ].

A predictive model of heat transfer and film condensation on horizontal finned tubes was presented. It was assumed that the film flows under the action of surface tension forces in the fin zone and under the influence of gravitational forces in the open channel zone between two rectangular fins [29JJ]. A mathematical model of heat transfer during film condensation of steam on a horizontal finned tube was presented. It was assumed that the liquid downflow in the fin zone is caused by surface tension, while the flow in the space between the fins is governed by gravitational forces [30JJ]. A theoretical model for film condensation on a horizontal low integral fin tube was presented. The analysis was extended to include the effects of condensate flow and heat transfer at the fin root tube surface [19JJ]. A method for predicting the average heat flow coefficient for film condensation on low integral fin tubes was presented which analyzes the surface tension drained condensated flow both above and below the flooding interface [18JJ]. Experimental measurements of liquid films on horizontal low finned tubes were made for R113, ethylene glycol and water. An analysis showed that some liquid is retained on the upper portion of the tube and the active area is increased by using a radius fillet at the fin base rather than a sharp corner which may enhance the condensation heat transfer [33JJ]. The Navier–Stokes equations were solved for condensate flowing over the sinusoidal fluted profile to find a volumetric flow rate [13JJ]. A kinematic wave equation describing the evolution of the film profile was obtained and solutions presented for laminar film condensation or evaporation on a vertical fluted cylinder. In the case of condensation, the majority of the film reaches a uniform thickness and consequently there is a significant improvement in heat transfer compared to the unfluted case where the film thickens continuously [27JJ].

A hydraulic jump mechanism was proposed to explain the wavy slug transition during condensation in a horizontal tube. Based on this mechanism, a simple empirical correlation was developed and shown to be consistent in magnitude and trend with data for different fluids and different tube diameters [36JJ]. A model for condensation heat transfer in stratified concurrent two-phase flow in a horizontal tube was developed that accounts for interfacial shear, axial pressure gradient, saturated temperature level, and driving temperature difference [8JJ]. A physical and a mathematical model were established to describe and upgrade the vapor phase resistance methods suggested by Bell and Ghaly. Effects of ripples at the interface and the angle along the bottom of the tube covered by liquid were included [24JJ]. Data were presented which show that two different condensing instabilities can exist in horizontal U-tube heat exchangers. The first instability is a cyclic type and the second is a condensate chugging or water hammer type [35JJ]. Condensation of water in an inclined thermosyphon was studied at angles from 0 to 80° from the vertical with heat transfer correlations developed [15JJ]. Results of correlations of experimental data on heat transfer coefficients from vapor condensing in a vertical tube were presented. When the vapor velocity is high, the condensate becomes entrained which significantly enhances the heat transfer coefficient [25JJ].

Direct contact condensation continues to receive considerable attention. Experiments were carried out in water to study the violent condensation shocks that occur in direct contact steam condensers at low steam flow rates. A characteristic feature of these shocks is a considerable amount of liquid entrainment into steam pockets which causes temporarily high condensation rates [10JJ]. Various optical flow visualization techniques were analyzed studying R113 condensing in water [28JJ]. Another study by the same authors looked at the condensation of R113 bubbles in water to determine the bubble size, shape and path for a theoretical model developed for the same phenomenon [31JJ]. A technique to separate condensate from a hydrophobic liquid condensing medium was proposed in which the bubbles rise from the floor initially while the more dense condensate sinks back to the floor. The method was tested using steam bubbles injected into liquid paraffin [34JJ]. The heat transfer coefficient was found to be nearly independent of steam superheat temperature when quiescent steam condenses on a slowly moving subcooled water film [6JJ]. A second study presented a theoretical model to predict the experimental measurements in the previous paper [7JJ]. The problem of heating a turbulent liquid jet by condensing vapor was analyzed using an integral modeling approach [42JJ]. An integral formulation was also used to predict the condensation of vapor on a liquid jet or falling sheet in the presence of a non-condensable gas. The results can be used to improve the design of cascade, curtain, or jet-type direct contact condensers [26JJ]. A theoretical analysis of direct contact hydroscopic condensation of cold vapor on hot liquid films was presented. The driving force for condensation is the difference between the partial pressure of water in liquid brine and in the condensing vapor. The condensation is also governed by simultaneous mass transfer mechanisms due to non-isothermal absorption with a possible opposing thermal driving force [5JJ]. The influence of heat transfer on the condensation rate of vapor phase molecules onto a charged nucleus was studied theoretically [40JJ]. A fully transient analysis was made of heat and mass transfer associated with a spray drop experiencing condensation. The model includes drop trajectory, gas phase, and liquid phase–time dependent hydrodynamics and heat/mass transport in the range of Reynolds number of 100 [22JJ]. Cloud formation and conversion of latent energy into mechanical energy in an unstable earth atmosphere was modeled. The growth of hail in a cloud was considered including the intensive wet growth phase [41JJ].

CHANGE OF PHASE—FREEZING AND MELTING

A one-dimensional heat transfer problem in a phase change slab, one side of which is isothermal while the other is insulated, was analyzed for the case of uniform, non-critical initial temperature in order to establish the additional time for change as compared to that for the case of the critical initial temperature [22JM]. A Stefan problem in which a semi-infinite molten material at the fusion temperature solidifies as a result of imperfect thermal contact with a cooler semi-infinite solid was considered [2JM]. The melting of a semi-infinite body subjected to a high energy flux at the surface was analyzed when heat conduction is governed by a hyperbolic equation [16JM]. Experiments were performed to determine the role of radiant energy absorption in melting in a vertical confined layer of semitransparent phase-change material (n-octadecane) [56JM]. A theoretical investigation was made of the process of free convection melting of a solid slab by an overlaying hot liquid pool [8JM]. The melting of a horizontal ice layer from above by an aqua-solvent with low solidification point was studied [47JM]. One-dimensional, conduction controlled solidification of initially overheated slabs and cylindrical and spherical shells with insulated inner walls was considered [7JM]. One-dimensional frost heave experiments were carried out on a Canadian silty soil under various conditions and it was established that segregational heave rate is strongly dependent on the rate of heat removal [31JM].

Experimental data for the liquid–solid interface position as a function of time and the wall temperature of a convectively cooled tube on which freezing occurs were obtained and compared with two theoretical predictions [10JM]. A new model of ice growth on a non-rotating cylinder was formulated which includes internal heat conduction, time dependence and solution using a high-level computer language specifically designed for simulating continuous systems [48JM]. The process of freeze coating of a polymeric melt on an axially moving continuous cylinder was studied numerically by a finite-difference method, taking into account heat convection from the melt to the freeze coat and spatial variation of the cylinder temperature [9JM]. The problem of one-dimensional inward solidification of a saturated liquid in a circular cylinder was investigated both experimentally and theoretically with the boundary surface maintained at a constant temperature [43JM]. A numerical analysis was conducted to investigate the process of axisymmetric, diffusion-controlled solidification in a thick walled cylindrical container using an alternating-direction implicit method to solve a nondimensionalized enthalpy formulation of the governing two-dimensional equations [45JM].

Two papers described the effects of aspect ratio and subcooling on the heat transfer during melting from a vertical cylinder [36JM, 37JM]. Experimental measurements were performed to investigate outward melting around a vertical cylinder embedded in a solid which is initially at its fusion temperature [46JM]. For various values of the Rayleigh, Stefan and Fourier numbers, the effects of natural convection on the volume and shape of the melt region and the heat transfer rate around a horizontal cylinder embedded in a frozen porous medium were evaluated [38JM]. A numerical investigation of melting inside a horizontal cylinder was conducted which included the effects of natural convection and the sinking of the remaining solid due to gravity during the phase change [39JM]. Melting of unrestrained ice in a horizontal cylindrical capsule was investigated experimentally to determine the interaction of fluid flow induced by the motion of the solid and natural convection with density inversion of the water–ice system [55JM]. An experimental study of melting in a vertical tube rotating about a colinear axis indicated that the rotation gives rise to considerably more rapid melting than that for no rotation, with the time required to achieve a given amount of melting being halved due to rotation [6JM]. An analysis was carried out for the temperature and velocity fields of a heat generating fluid confined in a frozen layer within a horizontal cylinder [33JM].

In companion papers, experiments were performed to obtain data for the heat transfer characteristics of latent thermal energy storage capsules [27JM] and analytical considerations were presented for the solidification process [28JM]. Semi-empirical laws and microscopic descriptions of transport behavior were integrated with principles of classical mixture theory to obtain a set of continuum conservation equations for binary, solid–liquid phase-change systems [3JM]. This model was used with a control volume-based, finite-difference scheme to investigate solidification of a binary aqueous ammonium chloride solution in a rectangular cavity [4JM]. The role of natural convection during melting of pure tin from a specially designed heater that formed a vertical wall of a rectangular cavity was studied experimentally [57JM].

A theoretical analysis was presented of the solidification of a liquid sphere, initially at its fusion temperature, subject to constant heat flux at the boundary [29JM]. A numerical method was used to analyze the rapid solidification of subcooled internally nucleated spheres, including capillarity and attachment kinetic effects [30JM]. A short-time analytical solution of radially symmetric inward solidification problems in spherical geometry was constructed using a new technique which assumes fictitious initial temperatures in some fictitious extensions of the actual regions and this solution was compared with a finite-difference numerical solution [19JM]. The analysis of gravity- and conduction-driven melting in a sphere was reported [1JM]. A note addressed the melting process within spherical enclosures with constant wall temperature and higher solid density for the case where no simplifying assumption for the film thickness is made [40JM].

The use of the boundary integral equation method for multidimensional problems with a moving phase-change interface was explored and the method was shown to be suited to heat transfer problems where the field equations are linear in each region and the boundary or interface are both highly irregular and nonlinear [41JM]. The role of natural and magnetically damped convection during the thermally controlled solidification of tin and aluminum alloys in a toroidal mould was studied [51JM]. A three-dimensional melting and solidification problem was solved in which a second layer of solid was added at variable rates [24JM]. A series of four papers addressed the topic of freezing and thawing of multi-dimensional shapes. In the first, experimental data obtained for 12 different shapes were presented [11JM]. Next, an assessment was made of the accuracy of numerical methods used in the prediction of the freezing and thawing times by comparing numerical and experimental results [12JM]. In the third and fourth papers, calculated and experimental data for multidimensional irregular shapes were used to assess various methodologies to include the effect of shape in empirical freezing and thawing time prediction methods [13JM, 14JM].

It was experimentally observed that two transition modes of ice shapes were formed inside a pipe containing water flow; one is a smooth transition mode and the other is a step mode [25JM, 26JM]. The shape of the solidification interface of the steady freezing of a liquid in a plane channel flow was theoretically found by taking the non-linear terms in the governing equations into account [23JM].

Experimental and numerical results were presented for thermal buoyancy-driven convection in a model that can be extrapolated to various vertical melt crystal growth configurations if additional convective effects induced by rotation gradients of the surface tension can be neglected [34JM]. Laminar flow, heat and mass transfer in a cylindrical floating zone were computed for co- and counter-rotation of the feed rod and crystal in the absence of Marangoni and natural convection for a crystal growth process [35JM]. Natural convection in the melt with vertical substrates in liquid phase epitaxial growth of silicon was investigated [52JM].

Several papers described phase-change problems related to industrial processes. A graphical method was proposed for the estimation of freezing times of foods with a high water content [42JM]. A method was described for calculating the temperature in a solidifying slab of molten material with greatly differing cooling rates on the inner and outer surfaces and results were presented which correspond to the industrial casting of polypropylene film [5JM]. A description was given for the application of the finite-element method to solidification problems concerning industrial casting processes and numerical examples were presented which substantiate the capabilities of a finite-element model, in both two and three dimensions [32JM]. An analysis of alloy solidification was used to illustrate a fixed domain variable time step computational technique [18JM]. A boundary integral approach to solidification problems for which the Stefan number and transition temperature depend on time was applied to a simple model of alloy solidification and some sample problems were solved [15JM]. Calculations of ribbon thickness and cooling rate for an Al–Cu alloy were presented based on a model for heat flow [17JM]. A thermal model was described of laser melting of coatings with an allowance made for convective heat exchange [58JM].

A pair of papers described three-dimensional numerical modeling of circulation and heat transfer in a glass melting tank. The first presented the numerical methodology to simulate the transport process [49JM]. In the second, the utility of the model, as coupled to the batch and combustion space sub-models, was demonstrated by presenting and discussing sample numerical results [50JM].

An enthalpy formulation for convection–diffusion phase change was developed. The essential feature of this formulation was that latent heat effects are isolated in a source term [53JM]. An enthalpy formulation based fixed-grid methodology was developed for the numerical solution of convection–diffusion controlled mushy region phase-change problems [54JM]. Short-time analytical solutions of temperature and moving boundary in two-dimensional two-phase freezing due to a cold spot were presented [20JM, 21JM]. An analysis of the interfacial shapes resulting from a periodic heat flux variation along the interface was examined for two cases of practical interest: (a) the amplitude of heat flux variation was small compared to the mean value; and (b) the wavelength of the imposed heat flux was much stronger than a characteristic length in the transverse direction [44JM].

RADIATION IN PARTICIPATING MEDIA AND SURFACE RADIATION

Radiation in participating media

One-dimensional calculations. The two-flux approximation for the hemispherical transmittance and the reflectance was re-examined for planar scattering media, and the results compared to the $P-1$ approximation [54K]. A scheme to successively improve the modified differential approximation of Olfe, was shown to be very fast and also to give accurate solutions for an optically thin medium [132K]. A new set of ordinates, which satisfy the half-range first moment of intensities, was proposed for the discrete ordinates method in one-dimensional scattering media. It was shown to be more accurate than the Gaussian quadrature of the same order [35K]. The Chebychev collocation method ($P_L T_N$ method), used to solve the spherical harmonics governing equations for an unbounded scattering medium, was extended to include transparent solid boundaries [55K].

The problem of multiple scattering in a semi-infinite half-space was examined with an expansion of the H-function in a power series in the albedo [89K]. A rigorous description of the n-times scattered radiation field and the specific intensity in the half-space was also found [90K, 91K]. The finite velocity of radiation transport through a medium was studied by modeling the heat transfer as a movement of thermal waves [86K].

The radiative transfer in a one-dimensional cylindrical enclosure with an absorbing, emitting, and isotropically scattering medium, was described by using expansion functions [118K]. An explicit solution for Abel's equation was presented, which arises when a set of data from a side view measurement of a cylindrical medium needs to be interpreted [116K]. A cell model for estimating the radiative heat transfer in a tube, laden with large non-scattering particles, was presented to supplement a Bouguer's law type of analysis [92K]. The radiative transfer in a concentric spherical enclosure filled with emitting, absorbing, and linear anisotropic scattering media, was analyzed using the $P-N$ approximation [119K].

Time-dependent and multidimensional radiation. The collocation and the Galerkin methods were used to study the radiative transfer in isotropically scattering, rectangular enclosures [117K]. The concept of improving a low order discrete ordinates solution by choosing a quadrature set which matches the half-range first moment of intensity, was illustrated for a two-dimensional enclosure of isotropic media [121K]. The measured radiation transmitted in an anisotropic scattering medium from a Gaussian laser beam was compared with the theoretical results for an isotropic medium with matched effective optical properties [77K]. The geometric mean transmittance in general absorbing, scattering multidimensional media was evaluated, to discuss the scattering correction to the Beer–Lambert law [135K].

Experimental measurements of exchange factors, made from enclosures containing near isotropic scatterers, allow furnace calculations where it is impractical to compute the factors algebraically [65K]. A generalization of a one-dimensional quasi-diffusion formulation provided the basis for an efficient numerical method for radiative transfer analysis in a two-dimensional disk geometry [110K]. Generalized, exact expressions for the source function, the intensity, and the radiative flux were given for an arbitrary absorbing, emitting, and isotropically scattering finite medium exposed to non-diffuse radiation [62K]. Reference [21K] proposed an extended differential approximation in an invariant three-dimensional form, which included anisotropic scattering. A double Fourier transform of the source function integral equation for a three-dimensional, rectangular, anisotropic scattering medium with collimated incidence, was shown related to the equation for a two-dimensional cylindrical medium with Bessel-varying collimated radiation [22K].

Time-dependent radiative transfer was the topic of the following papers. Reference [111K] developed an integral equation of transfer, which included a time-dependent absorption–re-emission term and an instantaneous scattering term. The formal solutions of the time-dependent radiative transfer equation, in an inhomogeneously emitting and absorbing slab, used the method of integration along its characteristics [72K]. The integral form of the time-dependent transfer equation for an inhomogeneous spherical medium was also presented [73K]. The theory of characteristics was also used to consider the problem of moving boundaries of inhomogeneous, absorbing and emitting media [74K].

Radiation in gas–particle mixtures. The normal spectral emittance of a one-dimensional planar mixture of hot gas and particles flowing between cooled walls was measured. Data were reported for mixtures of gaseous CO_2, N_2, and solid BNi-2. The results clearly show an extension of the 4.3 μm CO_2 band wings due to particle scattering [105K]. The Case normal mode expansion technique was used to study the interactions between the non-gray gases and the scattering particles in an isothermal planar layer. The effect of the particles is to shield the gas emittance in most cases [41K]. See also the comments in refs. [41K, 94K, 104K].

The problem of gray isotropic scattering particles combined with spectral gases was considered, and the possibility of directly measuring the special source functions in the medium were explored [124K]. The enhancement in the heat transfer, when a solid plate is inserted in a high temperature CO_2 gas in a laminar flow, was reported to be as much as 80% [48K]. Other studies dealing with gas–particle interactions are included in the following sections on radiation combined with other modes of heat transfer.

Radiative transfer in scattering media. The radiative extinction characteristics of packed-sphere systems were predicted by considering both the independent and dependent scattering formulations [29K]. Radiative transfer in thermal insulation made of either hollow fibers or fibers coated with thin dielectric films, was calculated by using the single fiber characteristics based on the Mie theory. The hollow fiber was found to have a higher backscatter and extinction coefficient, while the coating usually does not enhance the extinction [127K]. An analytical procedure to approximate an arbitrary phase function, expanded in a Legendre polynomial series, by a Henyey–Greenstein approximation was presented [53K].

A two-particle model considered the plume of solid rockets to be composed of an overlapping conical cloud of an inner, hot, emitting and absorbing particle cloud, and an outer, cold, scattering particle cloud, and used a hybrid Monte Carlo, radiosity–irradiation technique [31K]. A two-phase model was developed to study the selective radiative preheating of aluminum particles, assumed to be absorbing, non-emitting, and anisotropically scattering, in composite solid propellant combustion [12K]. Reference [19K] evaluated the performance of the gas particle radiator concept for space use.

The small angle approximation was shown to adequately describe the multiple scattering close to a beam incident on a turbid medium [37K]. Comparisons with a Monte Carlo simulation show the limits of the small angle scattering theory to be approximately 8–10 in optical depth [69K]. Reference [126K] used the small angle approximation to study the radiative transfer of a Gaussian beam propagating in a forward scattering medium. The Kubelka–Munk theory for moderately dense particle systems was re-examined, and some new Kubelka–Munk equations were proposed [61K].

The Rayleigh–Debye approximation was used to solve the problem of scattering by an ensemble of arbitrarily shaped particles [97K]. An improved computational method for determining the scattering, the absorption, and the internal field structure of thin flat disks was presented [131K]. Simple models, for predicting the scattering from a sphere in contact with a mirror surface, were compared with experimental results for polystyrene spheres [76K]. Measurements of scattering from a glass fiber parallel to a mirror, were found to compare well with the calculations for two parallel fibers, even when the mirror was not perfect [93K]. The predicted spatial distributions of the near-field and internal *E–M* intensities for large dielectric cylinders and spheres were verified experimentally using the fluorescence technique [7K]. Exact and approximate analytical expressions for the intensity within dielectric spheres was presented, based on the rigorous Mie theory [11K].

Radiation combined with conduction–convection

Radiation–conduction. The steady-state radiation and conduction in a two-layer, absorbing, emitting, and isotropic scattering slab with transparent interface was numerically studied [49K]. The effect of scattering anisotropy and albedo on the radiation and conduction heat transfer in a non-stationary system of flat, absorbing–emitting layers was studied [87K]. Radiation and conduction heat transfer between plane parallel plates, containing a mixture of non-gray gases and soot, was numerically calculated using the weighted sum of gray gases model with zonal analysis. The radiative transfer due to the presence of soot was found to dominate the heat transfer [106K]. A numerical solution of the problem of radiative and conductive cooling of hydroxyl-bearing glasses was compared with the measured surface temperatures of different quartz glass during vacuum cooling [36K].

The analytical results for transient conduction and radiation, obtained by using the discrete ordinates method and a finite-differenced energy equation, were compared with the experimental data for total heat transfer through fiberglass insulation. The study showed the effect of foil radiant barriers to reduce the heat transfer by about 42% [85K]. The unsteady, combined radiation and conduction heat transfer in a gray, absorbing, emitting, and isotropically scattering planar layer between two diffuse parallel plates, was numerically analyzed by using the Gauss quadratures and the resolvent method, coupled with a finite-differenced energy equation [88K].

An iterative numerical method was proposed, for solving the unsteady equation of conduction and radiation in a planar, absorbing, emitting, and anisotropically scattering layer bounded by specularly reflecting walls [13K]. Transient and steady heat transfer by conduction and radiation in an absorbing, emitting, gray, planar slab with semitransparent walls, was analyzed with flux boundary conditions [39K]. A two-layer slab of absorbing, emitting, and isotropically scattering layers, bounded by opaque walls and subject to flux boundary conditions, was also considered [50K]. A transient, combined conduction and radiation problem was solved in an absorbing, emitting, and isotropically scattering sphere, by using the collocation method for the radiation and the implicit finite-difference scheme for the energy equation [122K].

The combined conduction and radiation in finite cylindrical enclosures, containing gray, absorbing, emitting, and scattering media, was studied using the discrete ordinates code DOT-IV and a finite-differenced energy equation code [133K]. A testing procedure was reported, which separates the contribution of the conduction in the gas, the conduction in the solid, and the absorbed and emitted radiation, and the scattered radiation, in the combined radiation and conduction heat transfer tests through insulating materials [3K]. The phase transition accompanying the unsteady radiation and conduction heat transfer, in a planar layer of semitransparent medium, was studied [14K]. Experimental measurements of the radiative melting rate of polycrystalline paraffin, were shown to compare well with the numerical predictions obtained by using the one-dimensional discrete ordinates radiation solution combined with conduction. The dominant effect of the crystallographic effect is in the multiple internal scattering of radiation during melting [130K].

Radiation–forced convection. An experimental procedure for determining the radiative heat transfer coefficient from a total heat transfer measurement, in a combined radiative and convective heat transfer environment, was described [114K]. A method of measuring the radiation contribution to the heat transfer in fluidized beds was presented [83K]. The concepts of lost heat and entropy were explored, and a dimensionless number for the entropy production introduced. These concepts were applied to problems involving boundary layer flow and quenched flames [4K]. The problems of calculating the radiative combined mode heat transfer were discussed for applications in the area of power engineering [103K].

The effect of radiation coupled with conduction and convection were studied for a thermally developing, circular pipe flow of non-gray gases and particles. The interactions between the particles and the gases were modeled by adding modified gas band absorptances to the particle hemispherical emittances [115K]. The radiative and the convective heat transfer in gas–soot mixtures flowing in black walled tubes, were analyzed by using the weighted sum of gray gases model and the zone method [2K]. The random statistical narrow-band model, along with the Curtis–Godson approximation, was applied in an analysis of coupled radiation and convection in a laminar planer flow of emitting and absorbing gas mixture. Comparisons with the results obtained using the exponential wide-band model showed that the wide-band results tend to overestimate the absorption and the emission from the H_2O at intermediate optical depths [109K].

Radiative transfer in a rarefied magnetogasdynamic Couette flow with axially variable wall temperature, was studied using a perturbation procedure when the wall temperature variations were small [8K]. A numerical study of the flow of air and particles inside a solar heated open cavity, used the PSI-Cell code to describe the gas–particle interaction, and the discrete ordinates method to describe the radiative transfer [34K]. A single particle, two-temperature model was used to investigate the transient heating of gas and soot mixture, as it expands in a solar cavity [128K]. The possibility, of attenuating the screening effect due to the heated gases ahead of an intense shock wave, was investigated for a finite layer of xenon [57K]. The effect of radiation heat transfer on the atmospheric aerosols, and their subsequent effect on the vertical development of the turbid layer of the atmosphere, was discussed [26K].

Thermal radiation combined with forced convection of particles in vacuum, where there is no conduction between the particles, was studied in the following papers. A transient analytical solution modeled the cooling droplets as absorbing and emitting particles in a plane layer, and identified three transient zones [99K]. The solution was modified by including the effects of high scattering [98K]. Separable solutions were obtained for the fully-developed cooling of a flowing, planar layer of hot particles, which emit, absorb, and scatter isotropically. Solutions for both uniform velocity profile [101K] and non-uniform velocity [100K] were presented.

Radiation–natural convection. Reference [129K] modeled a radiation induced, buoyancy driven flow in a rectangular enclosure, by solving a coupled two-dimensional continuity, momentum, and energy equations, where a one-dimensional radiation model was included. The coupled natural convection and radiation heat transfer from fins was studied, to show the improved performance of a fin configuration with a staggered array of discrete vertical fins, over the fins with U-shaped vertical channels [45K].

Radiation in combustion systems

Reference [125K] presented a review of the radiation heat transfer fundamentals and recent progresses in modeling it in combustion systems. An elementary radiation transfer model, using a single gas zone, was proposed to predict the heat transfer in furnaces [27K]. Calculations of the temperature fields in furnaces lead to a method for analyzing the global heat exchange by radiation and convection [44K].

The structure and the radiation properties of a turbulent, hydrogen–air diffusion flame were studied numerically and experimentally. The predictions using the laminar flamelet concept and the narrow band radiation models were in reasonably good agreement with the measurements. The turbulence–radiation interactions were found to be significant for such flames [43K]. Available data for a large-scale natural gas–air diffusion flame were used for comparison with the predicted flame structure, using the conserved-scalar formalism with the laminar flamelet concept. The radiation was calculated by the discrete-transfer method with the narrow band models for H_2O, CO_2, CH_4, and CO in the 1–6 μm wavelengths range [42K]. Reference [108K] studied the interactions between the radiation and the turbulence in flames. The interaction effects were small for a preheated methane–air mixture, but they were greater when the mixture was not preheated, and when the flame was long. A method for determining the radiant properties of the flame was described, which was based on measuring the emission at various angles to the flame [75K].

A mathematical model for predicting two-phase flow chemical reactions (single step chemical kinetics) and radiation (extension of the single phase six-flux model) was presented [58K]. A flare was modeled as a frustum of a cone, which was radiating as a uniform solid body [17K]. Closed form expressions for the geometric view factors, which can be used to estimate the thermal radiation field, or the fire hazard, around a large fire were given [71K].

Radiative ignition was studied numerically by integrating the source function integral by a quadrature technique, which subtracts the singularity. The Arrhenius heat generation was balanced by radiation, and the critical heat generation level for gray, absorbing, emitting, and isotropic scattering layers was found to depend on the optical depth, the albedo, and the activation energy [23K]. A transient solution showed that a higher activation energy was required for pure radiation than for pure conduction [24K].

The scattering and the absorption characteristics of agglomerated soot particulates, which can be modeled as a collection of Rayleigh scatterers, were predicted using an existing analytical solution. These results were used to evaluate an equivalent sphere concept for the cluster, and an equivalent refractive index concept. The equivalent refractive index values were found to be in close agreement with the Maxwell–Garnett theory for mixtures [30K].

Surface radiation

Reference [6K] demonstrated the thermal isolation capabilities of light weight radiation shields, which form large V-groove cavities. A new method of calculating the radiative transfer in a system of surfaces, converted the system of integral equations at each point of the surface, by applying the interpolation quadrature method [134K]. The analytically obtained emission characteristics of cylindrical radiators of infinite length were compared with the experimental results of tests on a cylindrical radiator of finite length [15K]. Tikhonov's regularization technique was used to numerically solve the inverse problem of determining the temperature distribution of a thermal radiator, when the total power spectrum is known [112K].

The thermal-structural response of orbiting trusses were shown to be significantly affected by the member self-shadowing [66K]. The effect of the specular reflection of solar radiation from spacecraft was analyzed with an efficient method for treating multiple reflections [32K]. Reference [82K] discussed the possible control of heat transfer rate by modifying surface emissivities.

The radiative cooling effect of the Earth's surface on the formation of the vertical stratification of the nocturnal boundary layer of the atmosphere was studied [70K]. The successive over-relaxation method, with projections for finite-element problems subject to non-linear radiation boundary conditions, were considered [51K]. A variational formulation was constructed to estimate the temperature distribution within a radiating body in space [25K]. The heat transfer and the fluid flow in a cylindrical enclosure, containing a gas layer over the liquid one, was computed when there was a hot spot on the top wall. Gas radiation was neglected, but the surface radiation was included in the analysis [1K].

Radiative properties

An improved transient calorimetric method for measuring the total hemispherical emittance, used guard wires designed to reduce the heat losses through thermocouple leads suspending the specimen [67K]. A method for calculating the effective emissivity distribution over a sample surface, based on the concept of exchange factors, was reported [113K]. The effect on the accuracy of the normal spectral emissivity measurements, due to the variations in the cavity wall temperature and emissivity, was discussed [64K]. A directional-total emissometer was described, and the data presented for some metals, solar absorbers, and dielectrics [102K]. The total normal emissivity of liquid sodium was measured radiometrically in the temperature range of 150–670°C [52K].

The infra-red absorptivity and the reflectivity of hot-pressed SiC was measured using a 40 W tunable laser source [95K]. Geometric optics were used to show that the absorption properties of particles and drops in the near infra-red were greatly affected by the presence of internal scatterers, e.g. bubbles and occlusions [123K]. The high temperature absorption coefficients of SF_6, NF_3, and NH_3 were measured at a CO_2 laser wavelength using a shock tube [59K]. The thermal insulation of windows was improved by adding a layer of infra-red absorbing gas mixture between them [33K].

Transmission measurements in single crystals of Al_2O_3, MgO, TiO_2, and ZrO_2 were used to obtain the infra-red absorption of these materials as a function of temperature [16K]. The extinction coefficient of a high purity fused silica, in the 10–12 μm wavelength region, was found to vary essentially linearly with increasing sample temperature [68K]. The spectral directional transmittance and reflectance measurements of fibrous layers of pure vitreous silica were obtained in the 2–14 μm and 2–40 μm ranges, using a grating monochrometer and a bolometer operating at the liquid helium temperature [46K]. A method for obtaining the absolute diffuse reflectance of a sample does not require an integrating sphere, but does require two powder samples that are very weak and strong absorbers [63K]. The reflection coefficients of polycrystalline MgO at 0.488, 0.633, 1.15, and 3.39 μm, at temperatures up to intense evaporation were reported [80K]. Reference [10K] presented the spectral hemispherical reflectance and transmittance measurements of human and bovine dental enamel.

The absorption and the scattering coefficients, and the phase function were evaluated for foam and fiber insulations [40K]. The measured Rayleigh scattering cross-sections of methane, nitrogen, and carbon dioxide showed no effect of incident laser pulse duration [60K]. Reference [78K] reported on an experimental study of light scattering from random rough surfaces.

A vapor deposited coating on the alloys, Inconel 617 and MA 956, was found to reduce the catalytic activity in a space shuttle re-entry like environment, while not affecting the surface emittance [20K]. The normal incidence, antireflection characteristics of an absorbing thin film on an absorbing substrate were compared with those of non-absorbing antireflection layers [5K]. A radiative cooling study using LOWTRAN 5 found that an SiO_2 coating of low emissivity prevented the formation of frost on a glass exposed to clear sky, while maintaining good transparency [47K].

The $P-1$ approximation was shown to be effective for obtaining the albedo and the asymmetry factor from hemispherical transmittance data, when the medium is highly scattering [56K]. A comparative analysis of the methods for solving the inverse problem of property determination from plane layer measurements, found that the diffusion method coincides with the asymptotic ones, when a layer is subject to diffuse illumination [81K]. The method of moments was used to formulate an algorithm for determining the properties of light diffusing materials by solving the inverse problem [120K].

Instruments

A new type of two-stage reflectometer, with an inverted non-imaging compound parabolic concentrator, was described for measuring the directional hemispherical reflectance [107K]. An integrating sphere arrangement for the directional-hemispherical reflectance measurements was reported in the 1–15 μm range [84K]. An absolute reflectometer, based on an integrating sphere, needs no standard reference surface and operates in the 0.8–2.5 μm range with a computer controlled circular variable filter [96K]. The performance of a moderate temperature emissometer and sample holder was evaluated, with corrections for the non-isothermal condition, the apparent emissivity of the cavity, and the reflected irradiance from the surroundings [79K].

Reference [9K] described the use of a low-cost Michelson interferometer as a Fourier transform spectrometer for the visible and the infra-red, with better than 1 cm^{-1} resolution. An expression for the optimal signal to noise ratio for linear phase lock amplifiers was derived [28K]. A cylindro-conical cavity, with theoretically evaluated emissivity, was used to calibrate the infra-red spectral radiation from gas-fired radiators [18K]. The emission in a cylindrical dispersion medium was studied with the Monte Carlo method, in connection with optical pyrometers [38K].

NUMERICAL METHODS

Many papers include the description and use of a numerical method. Here the papers that focus on the *application* of a numerical method are included in the appropriate category. Papers that emphasize the details of a numerical method are reviewed in this section. Reference [51N] presented a survey of the literature on numerical heat transfer published in 1984–1985.

Numerical calculation of heat conduction often requires the solution of the Poisson equation. A number of new techniques for doing this were reported. The use of a spreadsheet program for solving the two-dimensional heat conduction was described [17N]. Reference [9N] presented a collocation method for solving the non-linear Poisson equation, while a three-dimensional Poisson solver was compared with alternative methods [22N]. The least squares method for solving thermal problems was employed [37N]. An efficient algorithm for a nine-diagonal matrix was described [40N].

Attention was given to the smoothness of data in solving an inverse heat conduction problem [4N]. Deformable finite elements were used for the solution of the non-linear inverse heat conduction problem [33N]. Another treatment of the inverse heat conduction problem employed *B* splines [14N].

The accuracy of some improved finite-difference formulations of the heat conduction equation was discussed [6N]. Finite-difference solutions for heat conduction in spherical coordinates were considered [63N]. Reference [25N] presented a practical time integration method for unsteady heat conduction. The use of three-dimensional finite elements for heat conduction was discussed [58N, 59N]. A collocation finite-element method was analyzed [28N]. The Stefan problem was solved by a Legendre spectral method [46N]. A technique of constructing interface elements for heat conduction was described [23N]. The boundary element method was applied to unsteady heat conduction [55N] and to anisotropic heat conduction [5N].

The finite-element methodology was used to perform a unified thermal-structural analysis [60N–62N]. The boundary integral analysis was employed for three-dimensional transient heat conduction [35N]. Electronic packages were analyzed by a time-dependent method [10N]. A finite-element model was used for the thermoelastic analysis of composite space structure [32N]. The unsteady surface element method was applied to the conjugate heat transfer from a strip heater [12N]. The duration of an unsteady process was predicted by a finite-difference method [8N]. Reference [54N] dealt with the transient temperature distribution in a thick annular disk with anisotropic conductivity.

The formulation of the combined convection and diffusion fluxes continues to be a crucial topic in both finite-difference and finite-element methods. The solution of the unsteady convection diffusion equation by the finite-element method was discussed [19N]. An assessment was presented for the characteristic-Galerkin method for advection-dominated problems [29N]. A numerical study [3N] pertained to the convection–diffusion reaction equations at large Damkohler numbers. Reference [30N] described some applications of the locally analytic scheme. A convective flux limiter was proposed for computational fluid dynamics [11N]. The upwind formulation was examined in the context of control volume finite-element methods [42N]. Compact operators were used in the numerical solution of reaction–diffusion equations [45N]. An extensive comparison of eleven discretization schemes was conducted for elliptic flow and heat transfer [38N].

The solution of the flow field is usually a prerequisite for the prediction of the convective heat transfer. A number of papers dealt with the numerical solution of the velocity field. A method was proposed [1N, 2N] for the solution of the Navier–Stokes equations in primitive variables using a non-staggered grid. Reference [24N] described a global relaxation procedure for compressible solutions of the Euler equation. Preconditioned methods were derived for solving the incompressible and low speed compressible flows

[64N]. The multigrid method was used to perform a vectorized flow calculation on a supercomputer [65N]. A combination of the multigrid method with the pressure correction methods was applied to viscous flows [7N]. Time-marching solutions were presented for incompressible internal flows [56N]. Reference [16N] proposed a new approach to the solution of the Navier–Stokes equations.

A number of finite-element methods were developed for the calculation of fluid flow. A control volume finite-element formulation was developed for flows in ducts of arbitrary cross-sections [43N, 44N]. In another development of the control volume finite-element method, refs. [47N, 48N] dealt with a different practise of using collocated variables. Some recirculating flows were simulated by the use of a finite-element method [41N]. Reference [57N] presented a review of the formulation of efficient finite-element codes for flows in regular domains. A vorticity–velocity formulation for high Reynolds numbers was proposed [36N], while the use of the penalty method for the Navier–Stokes equations was outlined [13N]. A variational approach for strong unsteady flows was suggested [52N]. A finite-element method for free and forced convection heat transfer was described [49N].

Among papers dealing with spectral methods, ref. [34N] described the development of a spectral method with a staggered grid for incompressible viscous flows. Also, pseudospectral methods were presented for the solution of multidimensional Navier–Stokes equations [26N, 27N]. Some research was reported on adaptive meshes. An adaptive-mesh finite-difference method was described for the Navier–Stokes equations [31N]. The concept of adaptive remeshing was applied to compressible flows [39N]. For the two-dimensional natural convection in an enclosure, a cubic spline numerical solution was presented [50N]. A numerical method was described for one-dimensional two-phase flow [53N]. Reference [15N] employed independent computational grids for each phase in a two-dimensional two-phase flow.

Monte Carlo solutions were obtained for turbulent flows in general orthogonal coordinates [18N]. The effect of space discretization on the accuracy of the numerical simulation of electrical furnaces was investigated [21N]. A numerical study was presented for the flow and heat transfer during high-pressure injection [20N].

TRANSPORT PROPERTIES

Work in this area continues to emphasize the measurement and prediction of thermal and transport properties for complex systems arising from recent technological development, particularly in the instance of thermal conductivity.

The hot-wire transient method was used to measure liquid thermal conductivity and to predict this property for families of alcohols and aldehydes [5P]. Using a shock tube, measures of thermal conductivity were obtained for $Ar–N_2$ and $N_2–O_2$ mixtures at high temperature [50P]. For solid materials a comparator technique provided continuous measurements of thermal conductivity [40P], while for translucent melts the coaxial cylinders method was used to gain information for this property [24P]. Photoacoustic measurements yielded thermal conductivity data for bulk polymers [46P] and the heat-pulse technique was employed to evaluate some conductive polymers [35P]. For fast, accurate measures of both thermal conductivity and diffusivity, ref. [39P] described the instrumentation to be used. Precise absolute measurements ($\pm 0.3\%$) of the thermal conductivity were given for helium and normal hydrogen [51P] and for the three gases argon, carbon dioxide and nitrous oxide [49P]. The latter paper noted all available high-temperature thermal conductivity data for carbon dioxide are in substantial error. Liquid argon thermal conductivities were reported around 100 K and pressures to 10 MPa using the transient hot-wire technique [9P]. The enhancement of thermal conductivity for pure fluids along the critical isochore was presented [43P]. By examining the heat conduction in single crystals of high purity aluminum nitride (AlN) ref. [71P] showed that the heat conduction is by phonons and that at the lowest temperatures the phonon mean-free path, l, is limited by boundary scattering.

Reflecting the diversity of materials and applications where thermal conductivity data were found to be important ref. [18P] reported on that property for various glass-reinforced plastics at temperatures below 80 K; ref. [3P] gave effective thermal conductivity values of coal ash at moderate to high temperatures and ref. [73P] measured the effective thermal conductivity of dispersed materials. Thermal conductivity of liquid hydrogen filled foam was reported in ref. [13P] and the study of transient conductivity in tellurium thin films in ref. [56P]. The absorption of water vapor by granular metal films induced variations on conductivity [52P] and the presence of thick anodic coatings on aluminum influences the thermal conductivity of that system [55P]. A laboratory made thermal conductivity probe was used to measure the effective thermal conductivity of food-grains at normal and different interstitial air pressures [70P]. For molten alkali halides and their mixtures the variation of thermal conductivity with temperature was measured using the coaxial cylinders method [72P]. Useful observations on the use of a thermal conductivity cell to measure the *para*-hydrogen concentration in a mixture of *para*- and *ortho*-hydrogen gas were given [8P].

Thermal diffusivity measurements were reported in a number of studies: for anisotropic materials [2P], for liquids by the laser flash method [22P], and by the photoacoustic cell method [58P]. The latter study considered the effect of sample bending. Using photon correlation spectroscopy thermal diffusivities were obtained for toluene and methanol over an extended range of temperatures and pressures [31P].

Correlation and predictive schemes continue to attract investigation. Predicting thermal conductivity for binary liquid mixtures on the basis of coordination number was reported [76P]. For liquids under pressure the predictive methods were analyzed and a general correlation of thermal conductivity given [41P]. Certain higher fatty alcohols were studied at high state parameters with regard to their thermal conductivities [53P] and a new correlation of thermal conductivity applicable to vapor and saturated regions was presented [68P].

For engineering calculations a formula was proposed for determining the thermal conductivity of hydrogen-containing technical gases to 15% accuracy over the range 373–1273 K and 10–100% hydrogen by volume [75P]. An equation for the thermal conduction of gas dielectrics in an electromagnetic field was also given [74P].

Considering solids or systems containing solids ref. [37P] reported an inversion method for determining effective thermal conductivities of porous materials; ref. [69P] estimated the same property for loose two-phase systems assuming an effective continuous medium extends to loose multi-phase systems at normal pressures. A related study [26P] examined heat transfer in compressed metallic powders and used the similarity between the influence of porosity on thermal conductivity and compression pressure in order to obtain an effective value of the former.

Further work with composite materials considered their effective thermal conductivity with interfacial thermal barrier resistance [27P] and a thermal contact resistance between constituents [6P]; the use of composite sample configurations for determining the thermal conductivity under pressure [11P] and an attempt to deal with the general problem of two-dimensional, steady-state heat flow for composites with fibers at any angle to the imposed temperature using a model [36P].

For solid phase systems the thermal conductivity was studied for the following systems: aluminum oxide with cobalt concentration and temperature variation [47P], porous tungsten–copper and molybdenum–copper pseudoalloys [21P], silicon carbide whisker reinforced mullite [64P], multi-fraction reactor fuels [34P, 59P] and metals and 3He with special regard to the contributions of magnetic coupling [33P]. The current views on thermal conductivity and diffusivity data for oxide melts at high temperature were reviewed [79P].

Turning to more practical and complex systems, ref. [65P] studied the thermophysical properties of soil. Reference [42P] examined soil near a buried heat exchanger using *in situ* measurements of temperature profiles. The apparent thermal conductivity of local adobe building material was reported [25P]. For food and food components ref. [54P] simultaneously identified the thermophysical properties of water-containing foods, ref. [4P] gave the 'intrinsic' thermal conductivities of basic food components while refs. [29P, 62P], reported on the thermal properties of frozen food and food, respectively. Heat transfer in insulating materials and the practical performance limits for such materials provided an insight into likely new materials and research areas [14P].

Flux calorimetry [15P, 16P], was used for measuring the thermal properties of solid materials. An instrument and technique for determining similar properties for foam-type insulation materials was given in ref. [67P]. The heat-pulse method was used in the instance of thin films [7P]. For estimating thermophysical and transport properties ref. [23P] described a non-linear least-squares method and ref. [77P] used the Leonard–Jones $(n, 6)$ model.

For selected systems transport property data were given for fluids of cryogenic interest [28P], a glass-filled polymer composite [30P], electrolytic iron [80P], liquid iron and nickel [60P], tungsten and graphite near their melting points [66P], graphite [19P] and special n-type and p-type alloys [1P].

Only limited work in the area of diffusion can be reported. A new apparatus for measuring steady-state diffusion was described [48P]; another was used to measure the thermodiffusion factor and determine the optimal conditions for separation in a thermal diffusion column [44P]. Other measurements dealt with diffusion and thermal diffusion in binary mixtures of methane with noble gases and of argon with krypton [20P]. For diffusion calculations involving wall reflection and low density a simple formula was given [10P].

Work on fluid viscosity is also limited. For measuring liquid viscosity up to 300 MPa and 400 K a torsionally vibrating quartz crystal was used [78P], details of a precision capillary viscometer were described [17P] and the viscosity of copper in shock loading was measured [61P].

The relationship between the equation of state of a liquid in general form and the thermal properties of liquids and liquid solutions was considered useful in predicting the latter [38P]. Also described was an improved corresponding states model for the prediction of oil and gas viscosities and thermal conductivities [57P].

Transient hot-wire measurements provided the basis for determining the heat capacity at constant pressure of fluids [63P]. For fluids and their mixtures a semiautomated PvT facility was described [45P]. Specific data on vapor pressure, vapor–liquid phase boundary data and critical properties were given for refrigerant 152a [32P]. The speckle interferometer allowed thermal expansion measurements [12P] to be obtained.

HEAT TRANSFER APPLICATIONS

Heat pipes and heat exchangers

Two general papers on heat exchangers present a survey on heat exchanger software: "Tools for the Engineer" [6Q] and determine the "Maximum Potentialities and Optimal Organisation of Regenerative Heat Transfer" [32Q]. Included is how to obtain the highest temperature of the cold fluid when the matrix temperature is limited.

A larger group of papers offers new information on heat exchange to various *heat transfer surfaces*. Among them is a report describing test results on air-to-water copper finned-tube heat exchangers at low air side Reynolds numbers [24Q]. An extended Japanese study is concerned with heat transfer and friction loss of plate fin and tube heat exchangers at Reynolds numbers between 70 and 700 [14Q, 30Q, 44Q, 45Q]. Single row and multi-row (2–5) exchangers, axial and circumferential distribution of local heat transfer coefficients around the tube bundle and row by row performance was studied. Three types of flow were defined: developing flow in the first row, transition flow in the second row, and vortex flow in the third and the following rows. Average heat transfer coefficients measured in this study agreed well with published data. Analytical models to describe heat transfer and friction in an offset strip-fin heat exchanger were presented [27Q] and supported by experiments. Heat transfer coefficients in dimensionless parameters were also reported [17Q] for a helical recuperator. Measurements of a model in a wind tunnel [33Q] find offset strip fin superior to other parallel-plate surfaces. Reference [1Q] discussed fluid flow, residence time, power consumption, film thickness, heat transfer, and evaporation in a thin film scraped surface heat exchanger. Laminar flow through scraped surface heat exchangers [19Q] resulted in poor radial mixing and heat transfer, the onset of vortices improved mixing which is beneficial in the normal direction but unfavorable in the longitudinal direction. Heat transfer in a vertical tube and annulus countercurrent sodium heat exchanger was investigated [25Q] under combined forced and free convection. No effect of a surface film was observed.

A number of experimental studies investigated the detailed *local characteristics of flow and heat transfer* in heat exchangers. The cross-sectional and longitudinal variations of heat transfer in a reboiler tube bundle [2Q], temperature profiles in U-tube heat exchangers [48Q], and the effect of maldistribution on the performance of heat exchangers were investigated [36Q]. The last mentioned effect was usually found small for turbulent flow but can be large in laminar flow. A maldistribution of the flow can occur in countercurrent gas–solid heat exchangers even when their beds are homogeneous, but when local temperature differences are present [54Q]. Flow dispersion effects were studied [12Q] for a range from plug flow to perfect mixing. A paper reported on the effect of tube bank inclination [34Q]. Tests [53Q] on an industrial size shell-and-tube heat exchanger determined the influence of tube vibrations on performance.

Unsteady flow and the transient response in heat exchangers is reported at several places in the literature. It was analyzed numerically for a step change in inlet temperature and for mixed and unmixed flow through crossflow heat exchangers [26Q]. The transient temperature of the wall and the gases were presented in graphs [47Q] for a step change of the inlet temperature of crossflow heat exchangers. The effect of the thermal capacitance of the contained fluid on the performance of regenerators was analyzed [42Q] by Laplace transform and presented as a function of *NTU* and the heat capacity ratio of the fluids and walls. A computer model was presented [10Q] for the dynamic simulation of shell and tube heat exchangers including a number of start-up processes. Such an analysis is also based on the solution of integral equations [18Q] solved by successful approximations. Unsteady temperature profiles were described [57Q] for parallel-flow spiral heat exchangers including or excluding the heat capacity of the walls.

Performance calculations considering the cost per unit transfer area, optimum velocities, heat transfer coefficients, and heat transfer area were described for water to water heat exchangers [31Q], for regenerative heat exchangers [20Q], and for condensing heat exchangers [9Q]. Some of the analyses were confirmed by experiments. A microcomputer program [46Q] predicted off-design performance for liquid to liquid shell and tube heat exchangers.

Fouling of heat transfer surfaces was studied by experiments [11Q] and analysis [5Q] supported by experiments.

The synthesis of *heat exchanger networks* was described [13Q] including an illustration by two examples. How to determine the required number of shells for minimizing capital costs was treated [51Q]. A simple method assessed the influence of uncertainties in the thermal and flow parameters on the design of a heat exchanger [8Q].

The heat transfer performance was studied for a spray cooling pond [35Q], for a small heat exchanger using silver powder and cooling liquid helium [29Q], for a pebble bed with thermal storage [52Q], for a high temperature pebble regenerative heat exchanger [56Q], and for an earth tube heat exchanger [41Q].

A considerable number of papers were concerned with *heat pipes*. An analysis of air-to-water heat pipe heat exchangers was offered [3Q]. Heat transfer coefficients of helical heat pipe heat exchangers with roughened surfaces [21Q] and those of a cryogenic heat pipe with longitudinal capillary channels [28Q] were reported. Methods for design calculations of high temperature heat pipes were surveyed [50Q] treating as an example a sodium filled heat pipe. An experimental study [55Q] treated sodium heat pipes with mesh screen wires. Experiments and analysis [37Q] considered the heat transfer performance of axially grooved heat pipes including the capillary pumping limit. The working characteristics of an anti-gravity heat pipe filled with water and 1.82 m long was studied experimentally and analytically [39Q] for angles from $-90°$ to $90°$. The utility of heat pipe heat exchangers for a range between 50 and 350°C, filled with alcohol, freon, water, dowtherm, and diphenyl was investigated numerically [49Q]. An analysis [15Q] of published data on boiling heat transfer in heat pipe wicks found that none of the proposed prediction methods was satisfactory. The influence of small amounts of non-condensible gas in the condensation zone of a heat pipe was studied experimentally [38Q]. Experiments were also compared with analysis [50Q] on the thermal conductivity of metal cloth heat pipe wicks [40Q]. Agreement within 10% was obtained and the implication on wick development discussed.

Thermosyphon systems have found increasing interest. Axial heat conduction was included in a one-dimensional model for the study of transient conditions [16Q]. A similar analysis [7Q] assumed the quality of vapor to vary linearly with distance. The heat transfer limitation was discussed [43Q] in a vertical annular closed thermosyphon with small fill rate. Experiments determined the flow characteristics of an internal thermosyphon reboiler in a model manufactured out of quartz, filled with various fluids, and with solid particles used as tracer [22Q]. The study was supplemented by temperature measurements in a copper tube reboiler. A design method based on the results predicted two-phase flow and heat transfer in such equipment. Analysis and experiments determined the choking limit in countercurrent closed thermosyphons [4Q]. The instability in the operation of thermosyphon reboilers was removed by a new design [23Q]. The flow was studied by visualization with particles as tracers. The circulation rate, heat transfer rate, and fouling rate were also measured.

HEAT TRANSFER APPLICATIONS—GENERAL

Heat transfer processes related to the electronics industry were the subject of several papers. A finite-element analysis of a dual-in-line microelectronic package revealed that a complex three-dimensional temperature field exists within the package when it is air cooled [24S]. An engineering model used to investigate the dimensions of the heat sink necessary for power ICs showed that the transport of energy from the heat sink to the ambient was a weak function of the thickness but was strongly dependent on the areal dimensions [5S]. The transmission-line matrix (TLM) was used to evaluate the effects of a layer of solder between a semiconductor device and its package on the temperature distribution of the device [26S]. Mathematical models of the gas cooling of a wafer during ion implantation were shown to be in good agreement with experimental data [19S]. The heat transfer problem related to a modified chemical vapor deposition process was analyzed in the high Peclet number limit [9S]. A two-dimensional model of the heat spreading process in buried-heterostructure laser diodes was used to determine the axial temperature distributions in the diodes [43S]. Using both finite-element and finite-difference techniques, the heat conduction equation for two-layer coils in He II was solved for both steady-state and transient conditions in two dimensions to yield the heat flux at the conductor surface [20S].

A linear theory of heat conduction in an interference filter with an absorbing spacer was presented for the case where the source of heat is a Gaussian beam [2S]. Calculations of heat flow in an absorbing film deposited on a non-absorbing substrate were also performed for the case where the heat source is a Gaussian beam [1S].

The power industry continues to provide interesting and complex heat transfer problems. A numerical study was reported of flow and heat transfer in a CANDU-Type 19 rod fuel bundle [61S]. The heat balance integral method was used to obtain an approximate analytical solution of the problem of melting and evaporation during disruptions in magnetic fusion reactors [52S]. The presence of strong magnetic fields and of volumetric heat generation in the fusion reactor environment resulted in an unusual heat transfer situation for liquid metals, as compared to non-conducting coolants [58S]. Heat and mass transfer were combined with kinetics to analyze a coal particle undergoing pyrolysis [46S]. A procedure was developed for predicting the flow pattern, temperature distribution and heat flux patterns within the end fired cylindrical furnace (precombustion chamber) in large capacity boilers fueled with pulverized coal [56S]. A comparison of calculated and experimental results showed that a computer model was capable of reproducing the main features of the complex flow and temperature fields past cooling towers, including the downwash effects at strong cross winds [16S]. Numerical results of the heat transfer phenomena around a high-level radioactive waste repository described the effects of the ground water flow, heat transfer and the latent heat of vaporization on the temperature distribution [59S]. The analysis of a double-pipe arrangement consisting of a hot supply pipe and a warm return pipe enclosed within a relatively cold, rectangular air filled trench indicated that there is an optimal separation distance between the pipes where the total rate of heat loss from the supply pipe is a minimum [44S]. A model allowed predictions of the thermal performance of spray cooling ponds in the case of zero wind velocity and results were utilized for a check of assumptions made by *NTU* models [40S].

A wide variety of industrial processes were investigated. A simple method for calculating radiant heat transfer in a directly heated industrial paper drier consisted of modeling the drier as an enclosure of three isothermal surfaces [13S]. The use of finite-element modeling of the heat transfer in plastics processing was described [38S]. A study of the cooling of a stretching sheet in a viscous flow showed that for a fixed Prandtl number the temperature decreases with an increase in the stretching speed [18S]. Two papers dealt with the flow behavior in a wall jet burner with the swirling flow and convective heat transfer to the burner tile modeled using a modified Prandtl analogy

[31S, 32S]. Heat flux and temperature distributions within a tall coke-oven flue were determined for various times during the coking process for several flue firing conditions [6S]. A variant regularization method was used to solve the inverse problem of radiative heat exchange between two surfaces in order to obtain the optimal mathematical design of high temperature radiators [50S]. An investigation was made of the quenching characteristics of polyalkylene glycol solutions in water. Relationships between the polyalkylene glycol, temperature and surface heat transfer coefficients in quenchants that contained up to 25% Aquaquench 1250 showed that the addition of 5% of the polymer reduces significantly the maximum surface heat transfer coefficient [4S]. Experimental and analytical techniques were developed for the determination of the interface heat transfer coefficient for non-isothermal processes and to study the effects of interface pressure, deformation and deformation rate on the heat transfer coefficient [54S]. An experimental study on the temperature increase in brittle materials was carried out using a rotating friction mill devised to produce submicrometer powder by the mutual friction grinding of two specimens composed of the same brittle materials [39S]. The dynamics and control of a heat integrated reaction/column system were studied [23S].

In order to establish the optimum cooling system for hot returned sand in metal casting processes, a mathematical model which includes simultaneous heat and mass transfer was constructed [45S]. Heat transfer coefficients were measured for suspensions of fine quartz sand or spherical polymer particles in a jacketed baffled kettle equipped with a cooling coil and a standard turbine, propeller or a pitched-turbine agitator [35S].

A review of the relevant experimental and theoretical knowledge dealing with the modes of heat transfer in internal combustion engines was presented [8S]. A multi-dimensional model, including turbulence, was used to predict the local flow, heat transfer and wall temperature of a direct injection diesel engine [27S]. A three-dimensional time-varying combustion-chamber model was described and the model used to show that the cyclic motion of the piston leads to an important heat loss not calculated by static models [29S]. The film cooling effectiveness and the local heat transfer coefficient were investigated both theoretically and experimentally on a gas turbine blade and the results were found to be in good agreement [30S]. Empirical formulae were developed for luminosity, radiation and convection under idling and full load conditions in a gas turbine combustor [41S]. An improved phenomenological heat transfer model was presented to describe the erosive burning flow process in composite solid-propellant rocket motors having propellant grains of large length-to-diameter ratios [22S].

A review was presented of some approximate methods used in the aerodynamic heating analysis [15S]. Based on heat transfer considerations, it is found that the near double cone with a flat nose is an attractive aerodynamic shape for Earth orbit re-entry vehicles [62S].

Two papers dealt with heat transfer problems related to bio-engineering. A simplified one-dimensional quantitative model of peripheral tissue energy exchange was developed for application in limb and whole body heat transfer studies [60S]. Three mathematical models were created of heat flow through the heart in order to better understand the origins of the temperature fluctuations in the pulmonary artery [28S].

A model was developed for the study of superficial thermal anomalies which frequently occur and remain for a long time after eruptive episodes which is valid for a thermal field having a magma body undergoing cooling as the heat source [17S]. Soil surface roughness provided a mechanism to alter soil reflectance and the surface energy balance [47S]. A thermal analysis of hydraulic fracturing based on variational methods provided a theoretical method for determining fracturing fluid temperature as a function of time and location during fracture growth [7S].

Heat transfer related to buildings and their environmental control systems lead to several papers. The steady-state heat losses from an infinitely long slab-on-ground floor insulated at its edges by horizontal insulation under the slab [37S] or by vertical insulation into the ground [36S] were calculated in two dimensions from a Fourier series solution of the temperature field in the ground. Both field data and finite-element calculations showed that natural convection in a block basement wall can be a significant factor contributing to heat losses [57S]. A model was developed, and checked experimentally, to allow reasonably accurate computer calculations for three-dimensional temperature distributions in sunlit, partially shaded windows [55S]. The surface heat fluxes of resistance heating elements were calculated for the case where natural convection occurs at the surface [25S]. A model was proposed for the simulation of a water-type heating floor on a terrace [21S]. One-dimensional fin theory was used to show that in many buildings fins on the exterior of the envelope do not increase the local rate of heat loss [11S]. A second law analysis of the optimum design and operation of a thermal energy storage system showed that a typical optimum system destroys approximately 70–90% of the entering availability and, therefore, has an extremely low thermodynamic efficiency [34S]. It was shown that a stratified thermal energy storage tank having eight compartments has an energy loss only one-fifth that of a totally mixed thermal storage tank [42S]. A thermosyphon with R113 as the working fluid employing fill ratios between 2 and 40% of the evaporator volume was experimentally and theoretically investigated [49S]. A comprehensive model of the steady-state and transient performance of a two-phase closed thermosyphon indicated that, for most systems, the governing time scale for system transients is the film residence time, which is typically much longer than the times required for viscous and thermal diffusion through the film [48S].

Individual papers dealing with a wide variety of applications were published. A non-dimensional heat transfer coefficient which included fluid conductivity, a length, fluid thermal capacity and velocity was proposed and the author stated that the quantity so formed varied much less than the Nusselt number with Reynolds and Prandtl numbers [14S]. The genesis of the statement of classical and generalized boundary conditions was considered in relation to parabolic and hyperbolic heat conduction equations [33S]. The irreversible generation of entropy for two limiting cases of combined forced convection heat and mass transfer in a two-dimensional channel were investigated [51S]. A numerical model was developed to study the two-dimensional laminar, natural convection flow in incandescent lamps by a finite volume solution of the steady continuity, Navier–Stokes and energy equations on a curvilinear body-fitted computational grid [12S]. A procedure was developed to calculate the thermal response of unconfined non-burning ceilings above growing fires [10S]. It was shown that countergradient heat flux (CGHF), where heat is transported from low to high temperature regions, arises in stably stratified parts of a flow if the dissipation of temperature fluctuations is too small to balance source terms for such fluctuations since in such cases CGHF converts potential energy into kinetic energy [53S]. Fluid motion and heat transfer of a high-viscosity fluid contained in a two-dimensional rectangular ship's tank subjected to oscillating motion were investigated by a finite-difference technique [3S].

SOLAR ENERGY

A considerable amount of work has been carried out in the past year developing and improving existing solar radiation models. The influence of Ångstrom parameters on modeled spectral solar irradiance was determined for conditions of high atmospheric turbidity [18T]. The normal direct irradiance can be expressed in terms of the individual transmittances of various atmospheric attenuators such as water and ozone, and layer thickness and α and β of Ångstrom's turbidity equation [49T]. An analytical model was proposed that expresses the hourly diffuse fraction of global irradiance in terms of hourly solar elevation and clearness index [79T]. An improved diffuse radiation model was presented which accounts for multiple interreflections between the ground and the atmosphere and has been found to agree well with experimental data [37T]. An empirical function fitting the diffuse radiation probability density function was determined from two sets of 20 year weather data which were used to determine more accurate long term average solar collector output [38T]. The calibration of a previously published clear sky model of diffuse sky radiance was made using measurements taken at Toronto in the springtime [39T]. Eight correlations for estimating the diffuse fraction of monthly daily horizontal global radiation and four correlations for estimating the monthly average daily horizontal global radiation were compared which shows that the diffuse correlations of Collares-Pereira and Rabl, Hay, Page and the daily horizontal radiation correlation of Rietveld give the best agreement with experimental data [8T, 10T]. A new simplified version of the Perez diffuse irradiance model for tilted surfaces was described in which five major changes were made from the original version [64T]. A method for computing the spectral and angular distribution of solar energy reaching any plane at or above the Earth's surface was developed [68T]. A quantitative evaluation of solar absorption in the Earth's atmosphere between 840 and 890 nm was made which describes the additional absorption found in this band over previous absorption models [19T]. A typical Ångstrom type correlation for estimating the monthly average daily horizontal global radiation was developed from radiation data from 48 worldwide locations [9T]. Correlations for estimating the monthly average daily global solar irradiation incident on a horizontal surface in arid or semi-arid regions were compared. The results indicate that the correlation of Bahel *et al.* gives the best results and that the correlations of Sayigh and Rietveld also produce satisfactory results [81T]. The generalized cumulative distribution curves of Liu and Jordan were found to be not suitable for tropical locations. This can be remedied by using a higher order probability density function [72T]. Four plane-of-array solar irradiance models were compared with data from three different locations. Of the four models compared, the Perez model was found to be the best [21T]. An hourly radiation model for inclined planes was presented which appears to perform well under both clear sky and overcast conditions [34T]. The importance of correct estimation of the radiation reflected by the ground and received on a tilted surface was demonstrated [41T]. An analytical model was developed which derives the probability density of hourly global irradiance from long term mean global irradiation [61T]. A simplified technique for computing long wave solar radiation was developed where the only input parameter is the amount of precipitable water vapor at any geographic location or season of the year [23T]. A bivariate periodic time series model for daily sequences of dry bulb air temperature and solar radiation was developed [17T]. A potential method to generate key daylight availability data from existing solar radiation data bases was proposed [65T].

The use of a silicon photodiode based rotating shadow band pyranometer was described including empirical correlations to mimic thermopile sensors. The silicon pyranometer provides results within 3% of conventional thermopile instruments [54T]. Corrections for shadow band shading of beam radiation on pyranometers can be improved using a two-component sky radiance model rather than an isotropic model [78T]. A solar radiation distribution sensor containing 24 radiation detectors positioned on a hemispherical body was developed to measure directional solar radiation emanating from the sky [4T]. Direct solar insulation can be approximated by measurements from two fixed pyranometers. Errors less than 3% were found for most of the tilt angles employed [46T]. A black-body pyrheliometer was developed that agrees to within 0.4% of conventional cavity type devices [93T].

An experimental facility was described which has been developed to test thermally absorbing coatings under controlled temperature conditions [47T]. The average directional solar absorptance, hemispherical thermal emittance and collector efficiencies of flat black paint and some agricultural products were determined experimentally by a calorimetric technique by using two similar flat plate air cooled solar collectors [5T]. Two methods of determination of the reflection and the solar radiation absorption coefficients by opaque surfaces were discussed. One of them makes use of quasi monochromatic light, in the other the so-called integrating sphere was applied in order to define the approximate values of the coefficients [70T]. Optical constants of copper sulfide films deposited on glass and aluminum were measured which showed the selective nature of these coatings. Films deposited on aluminum showed a maximum solar absorptivity of 0.89 and a minimum thermal emittance of 0.25 [33T]. Positioning and shielding of thermocouples located in a semi-transparent insulating material for temperature measurement were discussed and comparisons with predicted temperatures made [52T].

Studies of solar collectors and collection efficiency include the unification of three different theories concerning the ideal conversion of enclosed radiation that shows the relationship between the theories of Petela, Spanner and Jeter [12T]. An expression was derived for the exergetic efficiency of solar receivers which makes it possible to take into account both internal and external irreversible losses arising in the process of transforming the solar radiation into heat [25T]. An attempt was made to determine the optimum operating temperatures of a linear solar concentrator with a tubular receiver for maximum coefficient of performance of an absorption refrigeration system. The effects of absorber temperature, emissivity of absorber and wind loss coefficient on the heat loss factor were taken into account [53T]. Results were given from the testing of flat plate solar collectors with various honeycomb structures where the change in the incidence angle did not affect the efficiency of the collector [84T]. A theoretical analysis of an air heating solar collector with and without plastic Rasching rings in the air channel was performed using a heat transfer model based on the quasi-steady state condition [24T]. A method was suggested for determining the thermotechnical and aerodynamic characteristics of gravity solar air collectors which makes it possible to choose the most efficient design of the heat receiving surface [28T]. An improved thermal analysis of the heat transfer in the absorber plate of a liquid heating flat plate solar collector was presented [42T]. Instantaneous thermal efficiency was measured on a tubeless flat plate solar collector using R11 under two-phase boiling conditions [86T]. Experiments were performed to determine the net daily solar absorbed and night radiated energy from a selectively coated fin-on-tube absorber sheet [51T]. A mathematical model was presented which simulates the non-steady heat transfer processes in tubular solar collectors [50T]. An approximate solution was proposed for the thermal performance of an absorber tube in a trough collector. The resulting simple formula relates input and output variables directly and can be used to assist the temperature control of the collector [31T]. The steady-state temperature distribution and local natural convection heat transfer coefficients within a compound parabolic concentrator cavity were determined at various cavity inclination angles using a Mach–Zehnder interferometer [67T]. A comparison of several types of cylinder concentrators was made to determine their effect on the intensity distribution at the receiver plane [26T]. Square, uniform, real, and Gaussian solar disk intensity distributions were used to determine their effect on the optical performance of a cylindrical parabolic concentrator [59T]. An analytical investigation was made to study the performance of a stationary reflector/tracking absorber solar collector with a tubular absorber which identifies intensity concentration profiles along the absorber under different conditions [30T]. A quasi-transient heat transfer model was developed to analyze the thermal behavior of 'trumpet' concentrators which shows that simple design techniques can be used to maintain the temperature below safe limits under normal operation for many applications [85T]. Analysis of the thermal entrance region for fully-developed velocity in laminar flow coupled interaction between convection and radiation in an absorbing gray fluid was discussed [83T]. A numerical analysis of the mixed convection and radiant interchange in a plain channel radiant energy collection system that contains a participating medium was presented [20T]. A more precise formula for the heat transfer coefficient to calculate the heat balance of a solar desalination unit was given [29T]. The onset of thermal convection in a basin type solar still was studied using linear stability. The system was idealized as a horizontal layer of an absorbing, scattering and emitting liquid with a lower insulated rigid boundary and an upper convective free boundary subjected to uniform solar radiant heat [62T]. A transient analysis of a vertical solar still having two sides of absorbing surfaces covered with glass was made [45T]. The temperature distribution on the surface of a solar energy thermal receiver and its characteristic efficiency were determined taking into account heat losses through the insulation [1T]. An experimental study of a flowing film liquid direct absorption receiver was conducted which indicated heat transfer coefficients of about 3000 W m^{-2} $°C^{-1}$ [16T].

Solar ponds were studied which include a three-zone salt gradient solar pond model which considers each layer to behave as a steady-state flat plate solar collector [14T]. A numerical model was used to simulate the thermal performance of a salt gradient solar pond which was assumed to be cylindrical in shape with a thermal sink below and around it to simulate the heat losses to the earth [15T]. A mathematical model was developed to study the thermal behavior of salt gradient solar ponds under differential operational conditions. The convective heat loss, the heat loss to the atmosphere due to the evaporation through the surface of the pond and ground heat losses were accounted for in computing the efficiency of the pond [13T]. A transient model of a salt gradient solar pond was made for the case when high ambient and ground temperature exist all year round and clear sky weather conditions persist [35T]. The effect of reflectivity on the bottom of a solar pond was studied using a three-zone model. The presence of undissolved salt on the bottom has a substantial effect on the pond performance [82T]. Computer simulations of a Gel solar pond were carried out and parametric studies made to optimize the pond design for a specific application [90T].

The computation time was reduced in order of magnitude below methods requiring the solution of differential equations while achieving nearly the same results for studying solar air heating systems [36T]. Detailed thermal models of several types of solar air heaters made from plastic film were given [32T].

A method of correlating outdoor solar water heater test data so that long term performance can be evaluated was developed [56T]. An empirical method was developed to predict the thermal performance of thermosyphonic solar water heaters which use the concept of a constant temperature difference between the inlet and outlet water streams [60T]. A generalized procedure was developed to determine the effect of the absorber heat transfer on the performance of a water heating solar collector [6T]. A liquid heating system for a residence was simulated over a five-day period, which shows the temperature levels at various locations in the system [66T]. A theoretical and experimental study of a solar water heater was made that uses gravity assisted heat pipes with methanol as the working fluid [7T]. Heat pipe absorbers were found to perform more poorly in hot water heating systems but better for absorption applications than conventional flow through absorbers [40T]. A novel solar water heater was described in which the heat exchange tube is immersed into water containing a mixture of dyes [3T]. Thermal performance equations for collector efficiency and overall heat loss coefficient were derived for a closed-loop water heating system which uses an air heating solar collector and an air–water heat exchanger [11T]. A previous model for a two-phase water heater was modified to account for the diurnal variation of the heat transfer coefficient in the condenser [80T]. Various design and operating parameters were found to have little effect on the performance of a corrugated trickle water heater [48T].

An on site comparison of a sun space and a water hybrid solar device was carried out which shows that the user's influence due to visual and thermal comfort can have a large impact on their thermal performance [74T]. Experimental work on horizontal air flow rock beds was reported that shows the influence of natural convection on the effect of thermal conductivity of the experimental beds [71T]. A theoretical study of a composite Trombe–Michel wall showed that the addition of an interior insulated wall and convection channel improved the thermal performance of the wall and resulted in decreased mass compared with a conventional Trombe wall [94T]. A Markovian stochastic approach to the simulation of passive and hybrid solar devices was developed for predicting energy performance and thermal comfort in passive solar buildings [73T]. A comparison of the thermal performance of various types of south-facing water walls was made in terms of the heat flux entering an air conditioned space through these walls [58T]. The performance of active and passive rock bins were compared for passive solar heated houses in three climatic locations. It was shown that rock bins can reduce the amount of auxiliary energy required in the morning especially when night-setback thermostats are used [76T]. Auxiliary energy consumption during peak loads in passive solar residences during the winter can be reduced or eliminated only when thermal masses are well coupled to the interior and accurate weather forecasts can be used [75T]. A material designed for variable total internal reflection was utilized to allow radiation to be transmitted at some incidence angles but not at others. Applications include passive solar heating of buildings when direct sunlight would be transmitted in winter but not in summer [87T]. Automated window shutters were shown to make positive contributions to the design and performance of passive solar houses. An examination into the model equations revealed that for a given house design the effectiveness of the shutters is dictated mainly by the rate as well as the severity of the changes in meteorological variables [92T]. Calculation schemes for a thermal storage system in a greenhouse with shelves of substrate was given which includes a mathematical model of non-steady state heat transfer in layers of the system under consideration [88T]. A simple transient analysis of a greenhouse in winter was presented which shows that an increase in isothermal mass decreases the fluctuations in plant temperature [27T]. A simplified mathematical model was formulated for heat and mass transfer in multi-span greenhouses which was standardized and made convenient for solution on a computer [91T].

An analytical model for predicting the monthly and yearly thermal performance of stratified packed rock bed storage air heating systems was presented [2T]. The transient operation of a packed bed thermal energy storage medium was measured and compared with a one-dimensional conduction simulation model [22T]. A full scale residential sized test facility was used to determine the performance of a thermosyphon horizontal storage tank with and without a heat exchanger for freeze protection compared to a vertical tank with no heat exchanger [89T]. A simple rapid model for solving heat transfer problems for low temperature applications for a mixture of salt–water eutectic materials undergoing liquid–solid phase changes was developed with application to solar refrigeration systems [63T].

A new one-repetitive day simulation method was developed to predict the long term performance of solar energy systems that uses much less time and climatic information than conventional hourly simulation programs [69T]. Thermal test procedures for box-type solar cookers were developed which resulted in two figures of merit [57T]. Experiments were performed on a solar assisted open cycle desiccant–evaporative air conditioning system. A solar air heater, silica gel rotary regenerative desiccant wheel and an air washer comprise the primary components of this system [43T]. A design and performance analysis was made of a solar pond power plant that uses an organic Rankine cycle as the power cycle. Overall system performance was analyzed under varying load conditions [77T]. The optimum pond temperature and final conversion efficiency for maximum power production from a convecting solar pond power plant was determined numerically and the maximum efficiency was found to be less than 3% under the meteorological conditions of Japan [44T]. Heat transfer performance of the solar heater of an open cycle ocean thermal energy conversion system was experimentally studied using halogen lamps to simulate uniform flux [55T].

PLASMA HEAT TRANSFER

The relatively large number of papers concerned with heat transfer aspects in plasma processing and electric arc applications reflects the continuing interest in this field.

A modification of the conventional equilibrium approach for predicting products from plasma chemical reactions is in excellent agreement with experimental data with respect to product composition and yield [11U]. This method was applied in determining possible routes for thermal plasma synthesis of Si_3N_4. It was observed that the formation of liquid-phase free silicon in the neighborhood of 2500 K is very detrimental to Si_3N_4 yield [12U]. Studies of CO production in silent discharges indicated that CO production from CO_2 and hydrocarbons in air represents a serious obstacle for the development of a plasma-based air purification system [69U]. Ultrafine powders of ternary oxide systems may be synthesized from aqueous mixed solutions sprayed into an inductively coupled, thermal plasma [52U].

Experimental results of r.f. plasma decomposition studies of N_2O indicated that rotational temperatures increased with power at constant flow rates, reaching 450 K at 80 W and these temperatures were also found to depend on the temperature of the electrodes which were heated by plasma exposure [14U]. In a survey of the present state of research of the plasma spray process, the most important research problems were formulated [79U]. The predictions from a proposed heat transfer model for describing the heat flow during the arc spray process are in good agreement with experimental data. Therefore, this model may be used for determining the temperature history of arc-sprayed parts and for analyzing the problem of residual stresses [50U]. Results associated with modeling of thermal plasma jet reactors indicate that thermal plasmas show different mixing behavior in different gases and the coupling effects between plasmas and injected particles become important when the particle loading rate exceeds half of the plasma mass flow rate [40U]. Modeling results of fluid flow and heat transfer in plasma reactors show that a swirl flow plays an important role in providing mixing between the plasma jet and a reactant or diluent gas stream introduced through an annular port [18U]. The surface temperatures of metallic (Ni) or ceramic powders (ZrO_2, Al_2O) with mean diameters from 10 to 100 μm injected into a plasma jet reach surface temperatures in the range from 2000 to 4000 K measured by a two-color pyrometric method [45U]. A numerical model was developed for predicting the temperature history of metal particles injected into a low-pressure, supersonic, d.c. plasma jet [75U]. Studies of particle heating in r.f. discharges under dense loading conditions revealed severe cooling of the plasma due to the presence of particulates [55U]. Available data on heat transfer rates to small spheres in thermal plasma flows indicated good agreement in nitrogen up to 4000 K, but showed substantial deviations beyond this temperature [77U].

In a survey on Plasma Technology in Metallurgical Processing it was pointed out that the key to melting operations is the optimization of heat transfer to the charge which is achieved in the transferred arc configuration [57U]. *In situ* silicon-wafer temperature measurements during r.f. argon-ion plasma etching demonstrate that the measured heating and cooling curves can be fitted to a model which considers conductive heat losses only [33U]. Results of modeling work were presented, considering the temperature of a substrate during the deposition of a coating by the electric-arc process [49U]. A simple model for calculating plasma temperature profiles in atmospheric pressure microwave discharges was developed in connection with the optical fiber manufacturing process [4U]. An inductively-coupled, atmospheric-pressure plasma was combined with a low-pressure deposition chamber for the deposition of thin films. The high temperatures in the plasma are capable of melting and/or vaporizing even refractory materials [43U]. A plasma-materials test facility contains a mirror cell with high-field-side microwave injection and a heating power up to 0.8 kW at 2.45 GHz for plasma production [71U]. Studies of the corrosion resistance of Al alloy, Ni, and stainless steel coatings deposited on 1010 steel sample anodes using pulsed high-current vacuum arcs indicated that with optimal arc parameters, all three coating materials gave full corrosion protection during a 5 h salt-spray test, and Al and Ni coatings showed no signs of corrosion after a 48 h test [2U].

Laser scattering offers another possibility for measuring electron density and temperature profiles in high-density plasmas, and this method was successfully applied to the measurement of such profiles in transferred arcs [38U]. Using an approximate radiation transport model, theoretical predictions for a 2 kA d.c. nitrogen arc in a supersonic nozzle were in good agreement with experiments [78U]. Experiments with a multi-arc generator, comprised of stacked metal contact disks, revealed that the energy dissipated per gap increased as the contact disk mass decreased [59U]. The application of laser techniques to the investigation of high-current vacuum arcs revealed that increasing movements of the anodic melt produced large droplets several milliseconds after the arc terminates [26U]. Recovery studies of vacuum arcs after strong anode spot activity indicated that the recovery of constricted arcs with gross melting was considerably retarded [22U]. Spectrometric measurements of short metal arcs in air indicated a strong contraction of the arc near the electrodes with a width of approximately 40 μm [74U]. Vaporization of a silver anode in an arc discharge caused a significant temperature drop of the plasma and also a demixing effect [13U]. Modeling of an air arc column indicated strong modifications of the axial temperature and of the arc characteristics in the presence of Cu vapor [53U].

Theoretical predictions of the behavior of turbulent nitrogen plasma jets discharged into air were in good agreement with experiments, but the agreement was less satisfactory in the case of argon plasma jets [19U]. Investigations of the structure of a pulsed plasma jet indicated that this jet constituted a very high speed flow which enabled it to 'tunnel' its way into the surrounding dense air causing intense turbulence [64U]. Two-temperature modeling of an inductively coupled plasma showed that deviations from LTE become substantial under reduced pressure conditions, particularly in the energy addition region [48U].

Results for a cathode erosion study of an MPD arc thruster were presented for pulsed and steady-state operating modes including an explanation of the cathode attachment mechanisms for both operating modes [61U]. The results of electrode erosion studies on Cu cathodes suggest that erosion is primarily a thermal phenomenon, but the surface chemistry can greatly influence erosion rates by modifying the arc behavior [66U]. Results of measurements were reported, including surface temperature, gas pressure, heat fluxes and erosion in the cathode spot of zirconium and tungsten arc cathodes [17U]. Studies of cathode (Cu) erosion indicated that the arc erosion rate in argon is drastically reduced by the addition of only 1% N_2 which is due to an increase of the arc velocity in a magnetically driven arc [67U]. Modeling of the Cu vapor emission from the cathode of a diffused vacuum with a vapor temperature of 2000 K and an effective Cu vapor erosion rate of 3 $\mu g\ C^{-1}$, was in good agreement with the measured decay of the Cu vapor density from $5\times10^{17}\ m^{-3}$ at 300 μs before current-zero to $5\times10^{14}\ m^{-3}$ at 400 μs after current-zero [41U]. Experimental studies of the erosion rates of a Cu cathode in He, Ar, and SF_6 from 10^{-6} to 760 Torr indicated that the redeposited mass on the cathode was proportional to the cube root of the mass density of the gas [44U]. Lanthanum hexaboride (LaB_6) is a robust thermionic emitter for high cathode current densities. The total heating requirement is 202 W cm^{-2} at a cathode temperature of 1626°C [31U].

Studies of a pulsed vacuum arc showed that the peak heat flux into the anode as calculated from the temperature distribution compares reasonably well with the estimated energy flux calculated by using the anode region model of the first two authors of this paper. This heat flux is in the range from 7 to 8 kW cm^{-2} [28U]. The distribution of the current at the anode of an arc operated in vacuum or in a gas atmosphere is of fundamental importance for an understanding of the observed anode phenomena [21U]. Studies of the decaying arc response to voltage peaks indicated that the arc conductance variation for a short voltage pulse arises from electron heating [15U]. The plasma erosion opening switch (PEOS) can conduct large (MA) currents for several tens of nanoseconds before opening in less than 10 ns, generating megavolt-level voltages in the process [32U]. Investigations of Cu/Co contacts in vacuum interrupters subjected to an axial magnetic field showed that the arc concentrates and a part of the electrode melts at rather low currents. This however, does not affect the interrupting capability [51U]. A model of the prearcing behavior of an open fuse wire in air is based on the solution of the heat transfer equations, taking axial conduction, radial radiation, and free convection into account. Joule heating is the major heat source [1U]. An assessment was made of the various methods which have been developed for measuring temperatures in homogeneous optically thick plasmas [25U]. An iterative inversion was proposed of integrated spectral intensities emitted by an asymmetric and absorbing plasma [27U]. Results for partial and total absorption coefficients in a nitrogen plasma were reported for electron temperatures from 1 to 3 eV [68U]. A simplified spectrometric method for temperature measurements in the range from 2000 to 7000 K was proposed, based on the partially resolved 391 nm band of the N_2 molecule [16U].

Absolute continuum intensity measurements were reported for the emission from a low-voltage spark discharge [10U]. In the development of rotary auto-expansion SF_6 circuit breakers, optical diagnostics and pressure measurements were employed. The latter provided information on the energy transfer from the arc to the gas [39U]. Thermodynamic properties of air plasmas were calculated for pressures from 1 to 200 atm in a temperature range from 1000 to 30 000 K [3U]. Thermodynamic and transport properties for nylon and boric acid plasmas (ablation plasmas) were calculated for pressures from 1 to 10 atm over a temperature range from 5000 to 30 000 K [36U]. Atomic fluorine was produced by thermal dissociation in an arc in order to obtain information on thermal and electrical conductivity of hot fluorine [30U]. An efficient method was presented for determining the transport coefficients of plasmas generated from diatomic gases in an electron temperature range from 300 to 30 000 K and for degrees of ionization from 10^{-8} to 1 [23U]. Experimental results of plasma temperature and conductivity of a potassium-seeded combustion plasma system produced by introducing seed droplets of different sizes, were in agreement with a proposed model [20U]. One-dimensional steady-state transport equations were used to describe the equilibrium state of multiple species, cylindrically symmetric arcs. By writing the energy balance equation in the form of an action integral, it can be shown that the power dissipation is always a minimum thus proving Steenbeck's minimum principle [70U].

Experimental results of aluminum ablation studies considering the interaction of a KrF laser beam with the aluminum plasma were in good agreement with the predictions of a plasma ablation model based on inverse bremsstrahlung dominated absorption [29U]. Temporally resolved emission spectra of carbon ablation plasmas produced during laser hole boring by a 25 ns, 1 J ruby laser pulse indicated plasma temperatures of 12–14 eV [9U]. Studies of laser produced aluminum plasmas indicated the formation of a well-defined radiation heated zone at the rear (close to the ablation surface) of the shock wave [60U]. A power meter was constructed for measuring the power being deposited in transient, laser-induced plasmas [8U]. Results of ablation tests were reported, considering SiC and Si_3N_4 exposed to a free argon plasma jet [62U]. Results of analytical and experimental studies of local heat, mass, and radiative exchange were reported for thermally dissociated air passing through a cooled, slotted channel [7U]. Numerical calculations of the heat fluxes to a blunt body in a flow of dissociated nitrogen showed that the quenching has a substantial effect on the heat fluxes for hypersonic flying vehicles [6U].

The relative ease with which a low-pressure hydrogen stream may be heated in a microwave discharge suggests that such a system may be used as a thruster for spacecraft orbit raising purposes [47U]. Plasmas play an important role for the energy transfer during laser material processing [58U]. A new means for igniting explosive materials was described using a semiconductor bridge which produced a hot plasma when driven with a short, low-energy pulse [5U]. Breakup of the boundary layer by means of a corona discharge may lead to a substantial increase of the heat transfer coefficient in horizontal, parallel tube banks [37U]. Results of investigations of the high heat flux density on the surface of tungsten were presented for the electro-discharge machining process [42U].

Results of spectral-line reversal measurements of temperatures in combustion produced plasmas require corrections which reduce the measured temperatures and which depend strongly on the geometry of the system [73U]. The amplitude and the polarity of the potential difference between different temperature plasmas is controlled by the ion to electron thermal velocity ratio. The influence of the potential difference on the heat flow between different temperature plasmas was examined in the context of thermal insulation [35U].

The role of thermal radiation and conduction on the growth or decay of a wave in a magnetogasdynamic medium was studied for quasi-equilibrium and quasi-isotropic approximations of the radiation heat transfer equation [56U]. A comparison of hydrodynamic with hydromagnetic convection indicated that in the hydromagnetic case the variable fluid property has almost no effect on the flow and heat transfer characteristics, contrary to the situation in the hydrodynamic case [72U]. The use of He as a working gas in closed cycle MHD, instead of argon, proved to be advantageous from the viewpoint of both pressure loss and thermal performance [76U]. A numerical solution was obtained of the equations governing the fluid flow and heat transfer of an electrically conducting, viscous, compressible gas with variable properties in the presence of a uniform magnetic field [46U].

Studies of the pressure drop and heat transfer coefficient of He/Li annular mist flow in a rectangular duct with a transverse magnetic field at a pressure of 0.2 MPa suggested that the characteristics of the MHD pressure drop and of the heat transfer may be effectively applied to the cooling of high heat flux walls in strong magnetic fields [34U]. Zinc is currently produced by condensation of its vapor and, therefore, an MHD power plant could use the same technology [54U].

Experimental results of an electrohydrodynamically enhanced oil heater of annular cross-section showed that the heat transfer may increase more than 20 fold over the fully-developed laminar flow value, yet the pressure drop only increased 3 fold [24U]. Analytical results of studies of unsteady MHD flows near an asymmetric, three-dimensional stagnation point indicated that heat transfer and skin friction are reduced due to magnetic field and injection, and the effect of suction is just the opposite [65U]. Results of analytical studies were presented, considering flow and heat transfer in turbulent flow of a low concentration magnetorheological suspension in a channel of circular cross-section [63U].

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