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Heat transfer—a review of 1984 literature

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INTRODUCTION

THIS REVIEW surveys papers that have been published in the open refereed literature covering various fields of heat transfer during 1984. It is the intention to present a comprehensive survey; however, some sources may have been missed. For this we apologize.

A number of conferences dealt with, or included sessions on heat transfer during 1984.

Two sessions on film cooling, one session on analytical methods, and one on boundary-layer and air foil heat transfer were included in the program of the 29th International Gas Turbine Conference and Exhibit held at Amsterdam, The Netherlands, 3–7 June. Technical papers are available through the ASME order department.

A Heat Transfer Conference at the University of Leeds, U.K., 3–5 July was the first one of a series of U.K. national conferences on heat transfer planned to take place every four years alternating with the existing international heat transfer conference. The proceedings are contained in two volumes published by Pergamon Press. Volume 1 contains, among others, post dry-out and drop heat transfer, thermal hydraulic aspects of accidents and transients, reflood, reactor operational heat transfer, fouling mechanisms, regenerators and fixed beds, heat transfer networks. Volume 2 includes among others enhanced heat transfer, two-phase flow and boiling, high temperature systems and heat transfer in combustion systems.

The highlights of the 22nd National Heat Transfer Conference and Exhibition at Niagara Falls, U.S.A., 5–8 August were the Donald Q. Kern Award lecture on "two-phase flow in heat exchangers and pipe lines" by the recipient Duncan Chisholm and the Max Jakob Award lecture on "measurements of solids and gas motions in air fluidized beds" by the recipient Bei Tse Chao. A birthday celebration was arranged in honor of the 80th birthday of Ernst Eckert. Forty-eight technical sessions dealt with fundamental aspects of heat transfer and with applications like waste heat recovery, heat exchangers, solar energy heat transfer, industrial energy systems, reboilers, heat transfer in glass, and thermal storage heat transfer. Professional development and continuing education programs are already a well-established feature of these conferences. ASME papers are available in reprint and volume form and AIChE papers in the symposium series, Vol. 80, No. 236.

The XVI Symposium of the International Centre for Heat and Mass Transfer at Dubrovnik, Yugoslavia, 3–7 September 1984 was devoted to heat and mass transfer in fixed and fluidized beds and included among others sessions on measurement and application, modeling of fluidized bed reactors, fluidized bed combustion and gasification, and liquid and three-phase fluidization. It was preceded by an advanced course on fluidized bed combustion. The proceedings are contained in a volume distributed by Hemisphere Publishing Corporation, Washington, D.C.

The ETH, Zurich, Switzerland offered an International Seminar on Organic Rankine Cycle and Heat Pump Technology organized by the Verein Deutscher Ingenieure with co-sponsorship from France, Hungary, Japan, Switzerland and the U.S.A. The sessions were devoted to working fluid problems. Session IV was organized around heat exchangers, boilers and augmentation techniques. The proceedings are available as VDI Report No. 539.

The Winter Annual Meeting of the ASME at New Orleans, 9–14 December, included in its program 19 sessions on various topics of heat transfer together with a panel session on high pressure thermophysical data, two poster sessions and a special session on education in heat transfer. Heat transfer in biological media, ice and frost formation, coal slurry mixtures, in heat rejection systems, gas turbine hot sections, microelectronics fabrication and packaging were some special topics. The Heat Transfer Memorial Award was presented to Wen-Jei Yank at the Heat Transfer Luncheon, which featured as speaker R. G. Watts, talking on "heat transfer and the evolution and variations of the earth's climate". Preprints of the papers are available at ASME Publications Department and many of the papers will also be published in the *Journal of Heat Transfer*.

A number of books have become available during the past year. They are listed under references.

The following highlights illuminate development in heat transfer research during 1984.

Thermal simulation of machining processes comprised a significant portion of the research on conduction with less emphasis on contact resistance.

Channel flow research deals with increasingly complex problems involving fins and other augmentation devices, variable fluid properties, geometrical irregularities, conjugate heat transfer, and non-

Newtonian behavior. Several topics in boundary-layer and external flow responded to the need to better understand complex flow pattern and heat transfer in gas turbines, including the effects of larger disturbances on cylinders in crossflow (simulating air foil leading edges), and the effect of the wall on heat transfer from adjacent and perpendicular cylinders (simulating air foil root and tip regions).

A large number of computational papers on natural convection in enclosures filled with a saturated porous medium provide test cases for numerical analysis. They included onset of convection and channelling effects near walls. Unsaturated porous media, phase change systems, or fluidized beds found comparatively little attention.

Papers on experimental techniques and instrumentation were added to the Heat Transfer Review this year. Those chosen contain heat or mass transfer analysis or deal with the measurement of thermal transfer rates or thermal transport properties. Several of the techniques included electro-optics, e.g. holography, lasers.

Natural convection papers included multiphase flow in thermosyphons. Considerable interest was demonstrated in internal energy sources and in the effect of density maxima in fluids such as water.

The number of papers on boiling in nuclear reactors and on fundamental aspects of nucleate boiling decreased substantially. Interest remains strong, however, in boiling of mixtures and in enhanced surface boiling. A greater number of papers deal with film boiling and with the flashing of liquid to vapor upon depressurization. Research remains strong on phenomena in shell side condensation of shell-and-tube condensors. Topics include droplet slipping on the surface, film stability, boundary mixtures and the effects of oils. Several survey papers were offered on condensor performance. Freezing in the thermal entrance region of channel flow and simulations of continuous casting processes were popular topics in freezing and melting. The classical Stefan problem and natural convection-dominated melting continue to receive attention.

Radiative heat transfer calculations in multidimensional geometry were the topic of several papers. The coupling of radiation with conduction/convection and combustion is considered analytically and experimentally. There has also been an emphasis on obtaining relevant property data for various materials and radiating systems.

Developments in numerical methods are directed towards the treatment of arbitrary geometry, reduction of false diffusion errors and improvement of computational efficiency.

Research was focused on some novel methods and devices for measurement of thermal properties of materials. Of special interest were porous materials used in various heat transfer situations.

Over 70% of this year's papers dealing with heat exchangers range from measurements of local heat transfer coefficients to overall performance of exchangers or predicting their performance. Some papers deal with methods of enhancing exchanger performance or of offsetting some of the problems encountered in service, e.g. scaling or fouling of surfaces.

An increasing number of papers demonstrate a strong interest in plasma engineering dealing especially with plasma diagnostics, plasma generation and modeling, transport properties and plasma processing of materials.

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

CONDUCTION

A variety of theoretical studies of heat conduction have been reported. Some improved analytical solution techniques have been proposed with results given for some basic problems. Solutions are presented for transient and steady multidimensional problems ranging from metal cutting applications to combined conduction, convection and radiation.

The work on fundamentals included a new nonlinear theory of the constitutive equations for electrically and thermally conducting solids [14A]. Analytical solutions were developed for the hyperbolic heat conduction equation describing the wave nature of thermal energy transport in a finite slab with insulated boundaries and a localized volumetric energy sources [31A]. The solution is valid at short time intervals following the beginning of a transient and at temperatures near absolute zero when classical heat diffusion theory breaks down. Macroscopic transport properties were developed for a microscopically disordered system [24A]. The case of a periodic lattice with disorder in the transport properties at the level of individual bonds was considered. Measurements of the effective thermal diffusivity of a copper–niobium alloy were measured from 0 to 400°C [29A]. The rule of mixtures describes the data well. Extensions of available solution methods included the application of Green's function to linear, transient heat conduction problems [4A]. Two thermal boundary value conditions were incorporated in addition to the usual three. Applications in two and three dimensions were also outlined. A sign-count method for determining the roots of some of the transcendental equations associated with the analytic solution of transient heat conduction in a portion of a sphere was demonstrated [30A]. A simple boundary-element formulation employing a numerical solution method was proposed and applied to several examples of steady two-dimensional heat conduction in axisymmetric bodies [36A].

Several studies of transient conduction in homogeneous, isotropic media appeared. A closed-form solution for transient conduction in a slab with periodic surface temperature variation was presented with application to a rotary kiln [17A]. The temperature field in a thermoelastic slab with periodic surface temperatures was also given [12A]. The stability of a reactive slab with periodic surface heat flux was investigated [18A]. An approximate closed-form solution was described for a semi-infinite solid which experiences a surface heat flux pulse [33A]. Heat conduction in a semi-infinite solid with random surface heat flux variations was studied [10A]. The correlation between the interior and the surface conditions was found to decrease as the fourth power of the depth into the solid. Certain similarity was found to exist in the surface heat flux of wedges and semi-infinite solids imposed with a step change in surface temperature [35A]. Several papers considered the interaction of thermal and mechanical stresses which arise in machining processes or with internal heat generation. The transient one-dimensional temperature and stress distributions in a heat generating cylinder with variable thermal conductivity were presented [32A]. Green's function was used to obtain results for surface displacement and stresses due to a line heat source moving at constant speed across the surface of a thermoelastic half plane [1A]. Closed-form solutions were presented for the three-dimensional temperature distributions in a half plane with a moving two-dimensional heat source on the surface [34A]. Superposition could be used to obtain the solution when several discrete surface heat sources exist. Finite-element numerical techniques were used to study an inclined plane heat source moving along the surface of a half plane to estimate the shear-plane temperatures developed in orthogonal machining and grinding operations [11A].

A method of improving contact conductance by using a high conductivity metallic alloy that melts when in service but freezes for disassembly has been developed [9A]. The effect of contact resistance between longitudinal fins and a plane wall was studied [27A]. The contact resistance was found to be negligible when the area of perfect contact is greater than 10% of the total contact area.

Approximate solutions for one-dimensional transient heat conduction within a laminated material subjected to a harmonic surface heat flux were presented [7A]. A separation of variables, Fourier-series method was used to obtain solutions for transient heat conduction in a multilayered slab [15A]. Solutions for steady two-dimensional conduction in anisotropic media were given, using Green's function and a coordinate transformation [23A]. The boundary conditions can be mixed with temperatures prescribed on one surface and heat flux given on the remaining boundaries. Additions to a paper previously published by Atkinson were also reported [6A].

Transient one-dimensional problems include a numerical solution of inverse heat conduction with a radiative boundary condition [28A]. A study of the circular cylinder geometry was made to simulate the quenching of a rod [16A]. A procedure to estimate the spatial decay was presented [20A]. Simplified design charts were developed to approximate the cooling of various shaped solids in an isothermal, uniform convection environment [8A]. Various objects can be placed on the same chart if the characteristic length is chosen as the object's volume to surface area ratio.

Applications include the steady heat loss from a buried pipe network [13A]. Solutions using variable soil thermal conductivity approximate the effect of moisture on the soil thermal properties. The critical thickness of insulation for various shaped objects was determined for both convective and prescribed exterior surface temperature boundary conditions [21A]. A critical perimeter was found to be useful for irregularly shaped objects. The second law of thermodynamics was employed to optimize the number and location of a series of cooled shields located within porous insulation separating a hot and a cold body [5A].

Coupled heat transfer mechanisms or conjugate problems include coupled wall conduction and internal convection in a circular tube [2, 3A]. Conjugate conduction and convection on a circular pin fin has been studied [22A]. An experimental procedure for measuring the effective thermal conductivity of glasses at elevated temperatures was outlined [26A]. The coupling of conduction and radiation heat transfer through cells was studied experimentally with numerical and analytical solutions given for comparison [19A]. A study of a similar problem but including convection was also reported [25A].

CHANNEL FLOW

Confined flows have been studied in a number of different configurations. They include the classical geometries of circular tube and parallel plates; but attention is increasingly given to complex geometries that may enhance or impede heat transfer. The types of flow considered include laminar and turbulent flows, single- and multiphase situations and Newtonian and non-Newtonian behavior. Although the bulk of the literature deals with steady flows, some papers do focus on the time-dependent behavior.

Laminar heat transfer in the developing region of isothermal parallel plates is considered in [30B]. Reference [11B] deals with the parallel-plate geometry with a porous lining. The time scales of the turbulent fluid motion in a channel are investigated in [3B]. For a binary gas mixture, the kinetic phenomena in a channel are considered in [12B]. The unsteady conjugate heat transfer problem for a parallel plate channel is analyzed in [50B].

Among the many studies pertaining to the circular tube geometry, ref. [21B] deals with heat transfer in a laminar flow. The Graetz problem is discussed in [32B]. Reference [28B] considers the time-dependent behavior of the entrance region in a laminar pipe flow in response to a step change in the pumping pressure. The effect of suction or injection on the heat transfer in a turbulent pipe flow is investigated in [56B], while the influence of circumferential variation of heat flux is considered in [7B]. Measurements are reported in a circular tube, in which the turbulent flow is influenced by swirl [44B]. The axial conduction in the fluid and the pipe wall is considered for laminar flow in [13B, 42B] and for turbulent flow in [29B].

Numerical and experimental results are presented for the effect of roughness on heat transfer in tubes [14B]. Reference [24B] deals with the effect of direction of flow and tube position on heat transfer. The forced convection of supercritical n-heptane is investigated [25B]. Measurements are given for the heat transfer in a turbulent pipe flow downstream of an orifice [51B]. The turbulence statistics in a heated pipe flow are examined in the presence of suction [16B]. Reference [40B] deals with the turbulent transport in the transition flow region.

Among the studies directed towards the non-Newtonian behavior of flows, ref. [41B] reports the heat transfer enhancement in laminar slurry pipe flow. Heat transfer to drag-reducing turbulent pipe flows is analyzed in [57B] and to viscoelastic fluids in [22B]. Reference [15B] deals with heat transfer to laminar blood flow in a circular pipe. Stratified two-phase flow in circular tubes has been investigated [33B]. The heat and mass transfer in the presence of a mist in laminar duct flow is studied [20B].

Many channel flow papers deal with complex geometries that are encountered in engineering practice. The stability of divergent channel flows is numerically examined in [13B]. An experimental study of pin fins in a turning flow is reported in [47B]. The peripheral variation of wall temperature in a noncircular duct is experimentally found in [6B]. The effect of inlet conditions on turbulent heat transfer coefficients is investigated in [46B]. The introduction of internal circumferential fins in a *laminar* tube flow is shown to reduce the heat transfer instead of augmenting it [38B].

A turbulence model is used to predict the flow and heat transfer in a narrow isosceles triangular duct [37B]. Combined convection and radiation in rectangular ducts is considered [23B]. Fully-developed laminar flow and heat transfer in a triangular duct is analyzed in [34B]. Experiments have been conducted for laminar flow and heat transfer in an elliptical duct [2B]. The fully-developed heat transfer in an elliptic duct is also considered in [9B]. A comparison is made between symmetric and asymmetric periodic disturbances at the walls of a heated flow passage [48B]. Experiments are reported to determine the effect of the edge geometry in a duct flow [45B]. Turbulent flow heat transfer is measured for periodically converging–diverging tubes via a mass transfer analogy [45B]. Reference [18B] considers the effect of rib roughness on heat transfer and friction in channels. The local heat transfer downstream of an abrupt expansion in a circular channel is studied in [8B]. Fully-developed laminar heat transfer in circular sector ducts is analyzed in [53B].

A numerical calculation is presented for the heat transfer in a channel with two right-angled bends [5B]. The flow between two parallel disks is considered in [34B]. Laminar heat transfer in horizontal rectangular ducts is studied in [31B]. A numerical solution is given for the heat transfer in an annulus of periodically-varying cross section [35B]. An investigation deals with the heat transfer behavior downstream of a mixing junction [26B]. Flow and heat transfer in an in-line tube bank are solved numerically in [17B]. Reference [36B] presents an analytical solution for the secondary flow in a square duct. Laminar heat transfer in curved rectangular ducts is analyzed in [27B]. A general mathematical formulation for energy separation in a vortex tube is shown to compare well with experiments [49B]. Heat transfer from a heated concave wall is studied in [39B].

The influence of swirl-flow inducers on heat transfer in a circular duct is investigated in [10B]. Reference [55B] deals with heat transfer augmentation by twisted tapes. The combined use of twisted tapes and internally grooved surfaces is considered in [54B]. The absorption of thermal radiation in an open channel is investigated [19B]. The thermal–hydraulic characteristics in a liquid-metal fast breeder reactor plenum are studied in [52B].

BOUNDARY-LAYER AND EXTERNAL FLOWS

Laminar and transitional flows

Experimental results were presented for free molecular convection on fine metallic filaments [43C]. The dependence of accommodation coefficient on the surface state was found. The effect of buoyancy on Blasius flow over a heated horizontal plate was analyzed from the thermal stability point of view [49C].

Experiments were made to confirm the predicted locations of the onset of longitudinal vortices and the effect of the vortices on heat transfer. Measured and predicted heat flux distributions were compared for the Shuttle orbiter lower fuselage and lower wing centerspans [53C]. Experimental data for heat transfer to a film falling over horizontal cylinders was correlated by assuming complete mixing of the film [11C]. The correlation depends on Reynolds number and film thickness.

An approximate solution was presented for self-similar laminar boundary layers over plane and axisymmetric bodies [36C]. Nusselt numbers were predicted for various pressure gradients over a wide range of Prandtl number. Heat and momentum transport has been numerically evaluated for a pair of spheres in tandem [50C]. The drag coefficient and Nusselt number are always less than those of a single, isolated sphere—the effect is much stronger on the downstream sphere. The effect of heating or cooling on Görtler instability of a boundary layer on a concave wall was analyzed for short-wavelength disturbances [15C]. Critical disturbances are concentrated in thin, viscous layers near the middle of the boundary layer—heating destabilizes the short-wavelength disturbances while cooling does the opposite. Calculated critical Rayleigh numbers and wave numbers for thermally-destabilized boundary layers were found to be independent, or weakly dependent on free-stream acceleration [5C]. Laminar skin friction and surface heat flux on the rotationally oscillating cylinder in crossflow were analytically evaluated using a series method with perturbations [6C]. The unsteadiness effect on skin friction was large and increased with frequency whereas the effect on heat transfer was small near the separation point, and decreased with frequency. An analysis was presented for the heating of a particle which is suddenly introduced into a flowing fluid of different temperature [1C]. Asymptotic ($t \to \infty$) Nusselt numbers are considerably less than steady-state, isothermal-sphere values. The local Nusselt number is shown to become negative near the rear stagnation point of the sphere. The transient thermal response of a flat plate heated from below and cooled by convection above was analyzed [52C]. A parameter was identified which shows the relative conductive/convective effects. Numerical predictions of Space Shuttle heating were compared with flight data [19C]. Focus was on the effect of angle of attack and catalycity of the surface. An asymptotic solution of the Navier–Stokes equations for hypersonic flow behind bodies was presented [30C]. The solution allowed account of flow resistance and heat and mass transfer from the body. Laminar two-dimensional flow along an isothermal flat plate was analyzed to determine the dependence on fluid properties [16C]. Heat and momentum transfer analyses were presented for flow over surface-mounted parabolic cylinders and paraboloids of revolution—simulating dendrites [10C]. Diffusion extends a greater distance into the flow for parabolic cylinders than for paraboloids of revolution. Also, the boundary-layer assumptions were deemed inappropriate for dendritic surfaces. An analysis of submerged, swirled jets using the method of asymptotic expansion was given [44C]. Results were compared with experiments.

Boundary-layer transition on a heated, underwater body was experimentally investigated [26C]. The concentration of free particles was shown to affect transition by decreasing the effective Reynolds number. Experimental and numerical results were compared for the effect of cooling on transition with supersonic flow [28C]. Cooling stabilizes the first-mode disturbances, destabilizes the second-mode disturbances, and does not affect the acoustic wave interaction.

Turbulent and separated flows

The analogy between spectral distributions of temperature fluctuations and turbulent kinetic energy was experimentally examined [14C]. The analogy applies well except in stable atmospheric surface layers. A discussion of the history of the mixing length model for turbulent transport was presented [25C]. The relationship between heat transfer and skin friction was experimentally evaluated for turbulent wall jets [39C]. A new friction formulation was presented. Turbulence measurements were made in a heated wall jet on a convex wall to investigate the effect of curvature on turbulence structure [9C]. Locations of zero shear stress and streamwise heat flux were displaced, by curvature, further from the point of maximum velocity. The Stanton number is reduced more, by curvature, than the skin friction coefficient and temperature profiles depart from the flat-plate log law. The effect of concave curvature on turbulent boundary-layer heat transfer was experimentally evaluated using liquid crystal techniques [46C]. Large-scale streaks would appear and disappear at random but no stationary, Görtler-type vortices were observed. Experimental results were presented which show the unsteady heat transfer from a uniformly-heated flat plate in an oscillating air flow [12C]. The heat transfer coefficient depends upon the frequency of oscillation. A maximum value was found at a particular frequency. Results of experiments were given for leading edge heat transfer on cylinders with periodic variation of the angle of attack [31C]. The largest effect was a 10% augmentation at the nominal stagnation point. This effect was dependent on the Strouhal number, turbulence level and turbulence length scale. The thickness of the thermal boundary layer on the cylinder wall of a spark-ignition engine was measured using schlieren photographs [27C]. A maximum thickness of 2 mm is observed at the end of expansion. Reduced engine speed resulted in increased thickness. Measurements were presented for unsteady heat transfer from cylinders in an oscillating wake flow caused by an upstream cylinder [24C]. Maximum heat transfer was at the reattachment point of the shear layer which separated from the upstream cylinder.

An analysis was presented for cooling a low-heat-resistance stretching sheet moving through a fluid (a rejoinder) [3C]. Experimental results were given for heat transfer from a cylinder with close-fitting fabric in crossflow [48C]. A dependence on fabric thickness and state of contact was shown. Several fabric types were tested. The effect of finite heated plate width on heat transfer to turbulent flow was investigated [37C].

The effect of inserting heat transfer strips in a boundary layer was experimentally investigated [13C]. The distance between the strip and the wall and the angle of inclination of the strip were varied. Maximum augmentation was found at a particular separation distance and a 45° inclination. The augmentation of turbulent boundary-layer heat transfer on a flat plate due to three-dimensional protuberances was experimentally investigated [21C]. An optimum size/geometry was presented. An analysis was made to determine the optimum configuration of extended surfaces taking radiative interactions into consideration [51C]. Experiments made to evaluate the effects of length-to-diameter ratio and number of rows on the performance of short pin fins showed that the array-averaged performance was enhanced with increasing number of rows [4C]. Effects of pin fin spacing, height and channel height-to-length ratio were experimentally assessed [41C]. Increasing spacing was shown to be a means of reducing pressure drop while keeping heat transfer effective. Two potential geometries for pin fin arrays were experimentally evaluated [33C]. One array was found to augment heat transfer while decreasing pressure drop. Pin surface heat transfer coefficients were approximately twice end-wall values.

Experimental results were presented for evaluating the effects of freestream turbulence intensity on local heat transfer from a circular cylinder in crossflow [54C]. A correlation is proposed for this effect. Heat transfer from a long, thin hot-wire in high-speed subsonic flow was presented using a dimensionless approximation [20C]. Flow slip and thermal accommodation were included. Experiments were made to see the effects of variable properties, transverse wall curvature and freestream turbulence on cylinder external surfaces when the flow is axial [2C]. A correlation which includes these effects was presented. Heat transfer and flow behavior was experimentally investigated for flow over an elliptic cylinder with various angles of attack [40C]. Highest mean heat transfer values were found with angles of attack of 60–90°.

The effect of the wall on heat transfer from a cylinder perpendicular and adjacent to the wall was experimentally studied [17C]. Increases of 90–700% were observed very near the wall. The three-dimensional vortex structure effecting this increase was discussed. Local mass transfer and pressure coefficient data was taken on the side and the exposed end of a short cylinder perpendicular and adjacent to a flat plate [29C]. The effects of slenderness and the boundary-layer thickness were documented. Side-wall Nusselt numbers were reduced from those of an infinite cylinder due to separation. The heat transfer coefficient on the free end was higher than that of the two-dimensional cylinder. Measurements of quasi-local (axially) mass transfer coefficients were made in the wall–cylinder interaction region [47C]. Wall effects were observed within one cylinder diameter of the wall resulting in a decrease of the mass transfer rates of up to 15%.

Measurements of heat transfer from a heated cylinder in crossflow within an array of identical cylinders were performed [45C]. The addition of upstream rows of cylinders increased heat transfer by 50%. Fewer in-line rows were needed to effect this increase than staggered rows. An investigation of the promotion of heat transfer from a heated pipe by corona discharge was made [23C]. The pipe was put into an air jet and into a corona wind—the results were compared and it was found that the two were similar. Experiments and analysis of boundary-layer flow around a heated cylinder in crossflow showed that with increasing wall temperature, local Nusselt numbers increased more if the fluid were propane than if it were nitrogen [35C]. This is due to pyrolysis of propane and the stronger dependence of properties on temperature. The effect of freestream turbulence level on heat transfer from rectangular prisms in crossflow was experimentally investigated [32C]. Turbulence levels of 5% enhanced heat transfer by as much as 55% over that of laminar flow.

Local heat transfer coefficients were measured on a gas turbine nozzle guide vane surface [38C]. This data was presented as verification data for numerical code development. Short-duration heat transfer measurements were made on a flat plate and a gas turbine nozzle air foil at high freestream temperatures [22C]. Concave-surface heat transfer coefficients were high and convex-surface values were much lower than those for a flat plate.

Weak shock waves due to rapid heat addition at the boundary of a confined gas were investigated [7C]. The shock wave has the effect of a piston on the gas. The shock strength is directly related to the duration of heating. A linear acoustic wave is generated in a thick layer adjacent to the surface. The birth and evolution of a strong shock wave due to rapid boundary heating was next analyzed [8C]. The heat flux rises to full value with a modest multiple of the intermolecular collision time. The solution shows a steady shock wave propagating away from the boundary—supporting the moving piston analogy.

Flight data and design prediction values were compared for the shuttle orbiter base heating load [18C]. Contributions to the heat transfer came from the orbiter main engine and booster plume radiation, freestream air convective cooling, and reversed plume convective heating. A numerical study was made to determine the excessive heating in the tile-to-tile gap due to stepped tiles of the Shuttle Orbiter thermal protective system [42C]. Results show that the tolerance on step height must be tight, or filler material between tiles should be applied. Experimental results on a scale model of the Shuttle Orbiter were presented to show the effects of Reynolds number, Mach number and density ratio on heating distributions upon re-entry [34C]. Results show that the three are essentially negligible for the hypersonic portion of each orbiter flight.

FLOW WITH SEPARATED REGIONS

An analysis considered heat transfer around a heated circular cylinder in a rarified gas at low Mach number covering the range from slip flow to near free molecular flow with results which agree well with previous publications [10D]. Experiments on heat transfer in the separated regions of circular cylinders demonstrate [5D] that the r.m.s. fluctuating pressure at the downstream stagnation line is the dominant parameter determining heat transfer in the separated region. The wake region could be controlled by two small cylinders or a splitter plate. The frequency of vortex shedding in tube bundles was measured and found to be 2–5 times the Strouhal number [11D].

Heat transfer to the separated flow regions was also measured at different angles of attack for a rectangular prism with a side ratio of 4 : 1 [7D].

The relation

$$Nu_s = 0.0345\, Re_s^{0.46}\, (w/s)^{-0.142}$$

with s denoting the cavity depth and w its length describes the results obtained by a finite-difference analysis of laminar separated forced convection in rectangular cavities [4D]. A heat transfer study [9D] for the heated bottom of a cavity revealed three different regions for the dependence of Nusselt number on Reynolds number when the Reynolds number was based in the channel height downstream of the cavity.

Interesting photos visualizing the character of radial outward flow between two parallel disks [8D] demonstrate that the flow separates alternately from the two disk surfaces creating a vortex street. The flow was found to be rotationally symmetric. Heat transfer coefficients were much larger than values calculated for steady uniform flow.

The heat–mass transfer analogy is discussed for separated flow [6D]. A numerical analysis for flow through a pipe with abrupt expansion demonstrates [1D] that a three-layer model of turbulence gives best agreement with experimental results. A similar study of separating and reattaching flow [2D] concludes that a Reynolds-stress turbulence-closure gives better results than the k–ε model.

Experiments [3D] on temperature separation in vortex tubes (155 and 800 mm diam.) had the aim of determining the shortest length which still results in good separation. It was found that the efficiency can be as high for a length to diameter ratio of 6 as for longer tubes. It is pointed out that compressibility is essential for the energy separation.

HEAT TRANSFER IN POROUS MEDIA

Eighty per cent of the large number of papers in this area deal with convection in a saturated porous medium. Most of them are based on analysis or numerical simulation.

Thermal convection in a medium heated from below is treated extensively: analysis and experiments determine the time required for onset of thermal convection as a function of Rayleigh number [20DP]. The onset of thermal convection is also analyzed for a porous medium with continuous horizontal periodic stratification of the permeability [15DP]. Horizontal temperature gradients are found to inhibit natural convection [36DP]. A time-dependent temperature stratification influences the critical Rayleigh number depending on the ratio of porosity to permeability [21DP]. This Rayleigh number increases linearly with the ratio for values larger than 1000. Counter-rotating cells are formed in a porous medium bounded by a horizontal wall with hot and cold spots [28DP]. The height of the cells above the wall is equal to $\lambda Ra^{1/2}$ with λ denoting the distance between hot and cold spots and Ra denoting the Darcy Rayleigh number. The critical Rayleigh number and the heat transfer are analyzed for a porous medium consisting of alternate thin layers of high permeability and thick layers of small permeability [22DP].

Natural convection was also studied for rectangular enclosures [29DP]. Two cells form in such a cell when it is differentially heated in the horizontal direction. The temperature gradients are concentrated in thermal boundary layers at larger Rayleigh numbers. A numerical simulation [6DP] studied natural convection near 4°C in water filling the voids of a porous medium heated from below. The free surface on a liquid filling a porous slab heated from its sides is determined by numerical calculation for Rayleigh numbers up to 1000 [23DP]. Multicellular convection flow is created in a rectangular porous cavity with vertical walls at different temperatures for certain aspect ratios [31DP]. The result of a numerical calculation of natural convection in a rectangular porous cavity with a constant heat flux on one vertical wall and the other wall isothermally cooled could be expressed by the equation

$$\overline{Nu} = \text{const}\ Ra^m A^n$$

with A denoting the height-to-width ratio [30DP]. The flow was analyzed [10DP] for the corner region between a vertical heated wall and a lower adiabatic wall and for different angles between the two walls. Boundary layers are formed on both of these walls. Transient free convection about a vertical flat plate imbedded in a porous medium was studied [8DP] for a step increase in temperature or in surface heat flux. An analysis of forced convection in a packed bed near an impermeable boundary demonstrates a channelling effect with a velocity maximum near the wall [35DP]. The results reported for low Reynolds number describe thermal convection in a porous medium filling the space between two horizontal eccentric cylinders with the small cylinder either inside or outside of the larger one or the outside cylinder degenerating to a horizontal plane wall above the other cylinder [4DP]. Heat transfer in a horizontal eccentric annulous can be optimized by proper choice of the eccentricity [3DP]. Convective heat transfer was also analyzed for a pipe buried in a semi-infinite porous medium with and without fluid motion through the pipe wall [2DP]. The influence of injection or withdrawal of fluid on free convection around a vertical cylinder has been calculated for a prescribed constant wall temperature or heat flux [40DP]. Transient heat transfer between a fluid and a cylindrical porous bed is increased and the time of approach to steady state is decreased as the flow rate and particle diameter increase [18DP]. The dynamic response of heat transfer to an input pulse was measured and the results were compared with an analysis for a vertical test column with forced flow through it [11DP]. Axial dispersion was found to be important at low Reynolds numbers.

The effect of the ratio of the tube diameter d_t to the particle diameter d_p in the range 3–12 on the radial mass transport was studied experimentally and with a continuum model analysis. The results could be described by the following relation

$$Sh = \left[1.0\text{–}1.5\left(\frac{d_p}{d_t}\right)^{1/5}\right] Sc^{1/3}\, Re^{0.59}$$

in which Sh denotes the Sherwood number, Sc the Schmidt number and Re the Reynolds number [12DP]. The local distribution of the pressure coefficient and the heat transfer coefficient over the surface of a sphere in a bed of packed spheres has been measured [41DP]. An analysis of fluid flow and heat transfer at the edge of a packed bed is based on a model simulating the particles by a row of rectangular bars [9DP]. Results are obtained for Reynolds numbers from 0 to 100 and for Prandtl numbers from 0.72 to 7. The thermal conductance for a granular bed was measured over a wide temperature range for opaque particles at high temperature [42DP]. Axial effective thermal conductivities for flow at low rates were expressed as the sum of a conductivity without flow plus a term depending on the flow rate [37DP]. New correlations for the conductivity were presented for various gases.

A method was presented to calculate the influence of chemical reactions on radial heat transfer in fixed bed reactors [24DP]. It was found that in this case the Soret parameter plays a major role in determining the stability of the system [32DP]. Laser monitoring of the transfer processes in capillary porous bodies is studied analytically [25DP]. The transient response of a packed bed to thermal energy storage was analyzed for various Prandtl numbers [5DP]. The results which compare well with experiments indicate a pronounced effect of the void distribution. A new concept for thermal insulation in flow systems uses a porous segment in the duct causing back radiation [38DP]. It is proposed for the recovery of energy in furnaces or in chimneys.

The ratio of thermal to moisture diffusion coefficients for two unsaturated soils was obtained from the measured temperature and moisture fields [33DP]. Experiments on heat and mass transfer in unsaturated wood establish that total pressure differences in the air space contribute to water movement [1DP].

Semi-empirical equations describe the height of dry-out regions in packed beds heated from below [34DP]; they are based on a counter-current flow model in deep beds and on the boiling crisis in shallow beds and compare them with experimental results [19DP]. An analysis of heat convection on the drying of a porous semi-infinite space heated from a vertical wall assumes a sharp interface between the vapor layer at the wall and the liquid in the bulk of the fluid [17DP]. It thus disregards the capillary effects which make this boundary diffuse.

A small number of papers only treat heat transfer in a fluidized bed. An analysis studying heat transfer between the wall and a fluidized bed at high temperature concludes that radiation adds 15% to heat transfer for opaque particles and 40% for transparent particles at a bed temperature of 900° [13DP]. Wall-to-bed heat transfer coefficients in gas–liquid–solid fluidized beds were measured with flow of water and air through the bed [26DP]. Particles ranged from 0.61 to 6.9 mm in diameter and between 1330 and 3550 kg m^{-3} in density. Experiments measured the thermal resistance between the bed surface and adjacent particles in a fluidized bed for a very rapid transient process (10 ms) [16DP]. No difference was observed between the thermal resistance of a lightly fluidized and a packed bed. Heat transfer from a horizontal tube in a fluidized bed was found [27DP] to be different depending on whether the ratio of tube to particle diameter was smaller or larger than 10–20. Local heat transfer coefficients for a single horizontal tube in a larger particle fluidized bed at a temperature from 800–2000 K exhibit a maximum near 90° [14DP]. The undesirable effect of electric charges on heat transfer between a bed and an immersed wall can be overcome by adding a small amount of fine material [39DP]. An increase of the heat transfer coefficient up to 300% was obtained in experiments. Addition of coarse particles to a fine particle system improves fluidization and increases heat transfer [7DP]. The optimum is 25% coarse particles with seven times the diameter.

EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

Articles on experimental techniques and instrumentation which specifically include heat transfer or include the measurement of thermal diffusion properties or diffusion rates have been added this year to the heat transfer review.

A method for measuring local thermal conductivities of solids and porous media was presented.

Measurements were made such that thermal contact resistance errors cancelled [4E]. A method for measuring thermal conductivity of transparent liquids was presented which employs photon correlation spectroscopy [6E]. Measurement of production rate, thermal diffusivity and conductivity of solids using the principle of Laplace transform was presented [7E]. It has the advantage of being usable under arbitrary heating and cooling conditions. A method for designing experiments for measuring fixed-bed thermal transport properties was given which extends steady-state statistical design concepts to dynamic tests [11E]. A method which uses dynamic light scattering to measure thermal diffusivity of pure and binary fluids was discussed [13E]. Its use over an extended range of states was demonstrated. A simple high-temperature thermal diffusivity measuring apparatus was described which employs a light pipe, a long furnace and a differential thermocouple [16E]. A technique for measuring humidity above 100°C with a double-wick psychrometer was presented [8E].

Temperature gradients in liquids were measured using the phenomenon of laser speckle [14E]. Data was taken where a liquid was heated from below—heat transfer was by conduction. The use of liquid crystal thermography was demonstrated for heat transfer measurements in water tunnel flows [12E]. Error due to wall shear was addressed.

The effect of flow conditions and gage geometry were experimentally examined for a free-standing circular disk heat flux gage [18E]. A correlation of Nusselt number with angle of attack and Reynolds number was presented. A swollen polymer technique was presented for *in situ* measurements of local mass transfer rates [3E]. Holography and electronic speckle pattern were used to measure the degree of swelling. Precise natural convection heat transfer rates were obtained with balance and gradient methods [10E]. Construction and use of the apparatus to do so were discussed.

Theoretical and experimental evaluations of the frequency response of fine-wire thermocouples was presented for heated air flow [5E]. The influence of property variation in the surrounding gas was addressed and the effect of thermocouple geometry was discussed. The transfer functions for cold-wire temperature sensing probes were determined from a dynamic calibration system [9E]. They were then used to improve the dynamic response in turbulent boundary-layer temperature measurements. Experiments were made to demonstrate a new technique for measuring temperatures in flowing gas–solid suspensions with a thermocouple [2E]. Self-heating of ceramic-encapsulated rhodium–iron alloy resistance thermometers was investigated for low temperature operation [1E]. The thermometers were shown to be very stable with repeated thermal cycling.

Experimental results were presented which investigate the measurement of turbulent structure with hot-wires having wire lengths of about one-third the viscous length [15E]. A guide to the evaluation of uncertainties for hot-wire measurements was presented [17E]. Real-time data reduction techniques are shown to have lower uncertainties than time-averaging techniques.

NATURAL CONVECTION—INTERNAL FLOWS

Buoyancy-driven flows continue to be of great interest to the research community, serving as an excellent means for studying fluid-mechanics problems including the basic nature of turbulent flow and transition, as well as being a necessary component of a number of practical engineering problems. Studies on buoyancy-driven flow in differentially-heated plane horizontal, vertical and inclined layers remains of interest, including the effects of a density extremum such as occurs in water near 4°C. Heat transfer to fluids in nonplane cavities including annuli remains of interest. Double-diffusive convection, heat transfer in porous media, the effect of fires on flow, thermosyphons and mixed convection all have gained considerable attention recently.

Plane fluid layers with temperature differences across them approximate a number of physical systems, from windows to solar energy collectors, to planetary atmospheres; even flow in the interior layers of stars can be approximated by such a model. For some years, attention has been and continues to be directed towards horizontal layers heated from below. One key interest relates to getting a better numerical and physical understanding of turbulent flow. Interest has been accentuated recently with descriptions of physical phenomena involving transformation to chaos.

The energy method has been used to predict Nusselt number, temperature distribution and maximum velocity in a horizontal layer heated from below [34F]. Analysis indicates that for a Prandtl number greater than one, a square planform can result when a layer is heated from below if the wall conductivity is of the order of that of the fluid or smaller [35F]. A three-dimensional simulation of Bénard convection indicates the transition from laminar to chaotic flow [16F]. Linear theory leads to a prediction of the turbulence profile in thermal convection which agrees with measurements [28F]. Numerical and analytical predictions of convection in a rectangular layer agree with each other [41F]. The convection in a layer with stress-free boundaries can offer potential for detailed studies of post-stability flow (9F).

The interaction between two horizontal layers, one over the other, and separated by a partially-conducting horizontal plane was examined [11F]. The influence of vertical vorticity on Bénard convection has been described [50F]. The ratio of solid to liquid thickness in a horizontal layer freezing from above determines whether the flow pattern is hexagonal cells or rolls [17F]. Numerical study of convection in water near its maximum density indicates the influence of aspect ratio on transition [7F]. The effect of a density extremum stabilizes a layer of water heated from below [29F].

A linear analysis agrees with experimental results on the initial onset of flow for sudden heating from below [38F]. A nonlinear stability analysis predicts a planform of stable hexagons within a thin fluid layer having a sinusoidal variation of bottom wall temperature [59F]. For a horizontal layer having shear-free upper and lower surfaces and internal energy sources, the time for onset of flow following a decrease in upper surface temperature increases as the Prandtl number of the fluid decreases [39F].

Studies on differentially-heated rectangular layers where the temperature gradient is primarily in the horizontal direction, include stability studies and the influence of turbulence effects. The conditions under which steady state is approached by oscillatory conditions in a low-aspect-ratio layer have been explored [53F]. In a square cavity with differentially-heated walls, the k–ε model has been used to predict turbulent transport [45F]. In an open vertical channel with side wall heating, recirculating flow can be drawn into the channel from above [65F]. Relations show the optimal spacing in a vertical channel for heat removal in electronic system [3F]. Flow has been visualized in a cubical cavity, with a transparent top wall heated from any of its vertical walls [8F]; a relatively inactive core was observed surrounded by boundary layers on the walls.

A two-equation model for turbulent flow was extended to natural convection in internal flows [60F]. Visualization using liquid crystals has been useful in studying convection in cavities [57F]. Measurement and analysis indicate three-dimensional natural convection patterns in flow that occurs in glass-making furnaces [15F].

Numerical analysis shows the influence of a semicircular protuberance on the two-dimensional flow in a square cavity [37F]. In a low-aspect-ratio differentially-heated cavity, a vertical partition projecting part way across the channel can strongly influence the flow field [51F].

Measurements with inclined layers of fluid at a Rayleigh number of 2×10^6 show different flow regimes at different angles of inclination [33F]. A series of papers [30F–32F] on convection in an inclined layer with water near its density extremum show the flow pattern and temperature distribution, and provide heat transfer correlations from both experimental and numerical results. In a differentially-heated cavity, wall conduction can stabilize or destabilize the flow depending on the orientation of the heading and cooled surfaces [40F].

A number of studies have been directed toward buoyancy-driven flow inside circular cylinders or pipes. LDV measurements show a region of three-dimensional flow in a horizontal cylinder of low aspect-ratio with different end temperatures [61F]. A numerical solution for buoyancy-driven flows in a vertical tube with a temperature-dependent viscosity shows large effects from variable properties when properties of real fluids are used [72F]. The potential of reduced heat transfer coefficient in the supercritical region due to large variations in properties has been studied in vertical tube flow [47F]. Vortex rolls induced by corona discharge increase free convection inside a vertical cylinder [18F].

Buoyancy-driven flows are often important in the space between an object and an enclosure that surrounds it, such as the annulus between two cylinders, space between two spherical shells, etc. Visualization and numerical calculations indicate the flow and temperature distribution in a vertical annulus between two concentric cylinders in which the inner cylinder is partially heated [22F, 23F]. The effect of variable properties on the heat transfer across the annulus between concentric horizontal cylinders is small for moderate temperature differences [26F]. The transient time for natural convection to start in an annulus when one of the cylinders is suddenly heated is small [68F]. Streamlines indicate three-dimensional flow in the form of a coaxial double helix in an inclined cylindrical annulus [67F]. The Nusselt number Rayleigh number relationship has been determined for finned tubes in a circular container [5F]; there is little effect of the enclosure for diameter ratios of 25 or more. Convection in a spherical shell has been studied by numerical analysis [19F]; for a radius ratio > 41 the heat transfer is essentially equivalent to that from a single sphere in an infinite medium. A perturbation technique [58F] predicts three-dimensional steady convection in a spherical shell. Experiments with one cylinder inside another cylinder show that the Nusselt number is insensitive to the position and orientation of the inner cylinder [66F].

Studies on open and closed large-scale cavities have been used to simulate the progress of fires. A numerical model of buoyancy-driven combusting fluids is suitable for examining the progress of a fire in an enclosure [44F]. Fluid dynamics of large scale fires have been analyzed with a model that simulates the combustion process by a volume heat source [64F]. The velocity profile in a cavity opened on its side has been measured [25F]. The interaction of sprays with buoyant flows is strongly dependent on the relative momentum of the spray droplets and the buoyant flow [1F].

Studies on thermosyphons in which fluid passes through a continuous loop driven by buoyancy from localized heating, include single- and two-phase systems. The variation of friction and heat transfer in a toroidal natural circulation loop has been analyzed for laminar flow [48F]. An analysis of the stability of flow in a closed toroidal loop indicates transition to steady or chaotic flow as opposed to the periodic motion [24F]. A survey of the literature on two-phase thermosyphons has been reported [54F]. The maximum heat transfer in a change-of-phase thermosyphon with internal baffles has been measured to find the effect of area reduction on the flow [6F]. Relations have been developed for determining the maximum heat flux in an evaporating–condensing thermosyphon [70F]. A scale model of a pressurized water reactor was used to study the natural circulation heat removal following loss of pumped flow [63F].

Buoyancy-driven flows in porous media have been studied for a variety of geometries. Within a vertical annulus filled with porous material, the heat transfer in the boundary-layer region is only a weak function of aspect ratio [55F]. An analysis of higher-order corrections to the boundary-layer solutions were presented for laminar vertical plumes and flow along a vertical heated plate [36F]. Numerical analysis of heat transfer in saturated porous media with internal energy sources includes the effect of a liquid layer on top of the porous media [62F]. Flow in porous material with internal energy sources has been analyzed with an expansion technique for low Rayleigh number flow and a linearization method at high Rayleigh number [20F]. With an internal energy source in a horizontal annulus filled with porous media, the maximum temperature can be higher than that which would occur with pure conduction [71F]. A study of three-dimensional convection in a cubical box of porous media includes effects with fluids that have a maximum density at an intermediate temperature in the material [2F].

Double-diffusive convection occurs in fluids in which buoyancy forces are provided by two-diffusion phenomena, usually diffusion of heat due to temperature difference and diffusion of mass due to concentration difference. A conference summarized the state of knowledge and research activities on double-diffusive convection including a description of important applications of such flows [13F]. A theoretical analysis provides insight into thermohaline convection in containers of arbitrary shape [52F]. The development and stability of salt fingers which can occur when a layer of warm salty water is present above a cooler, fresher layer of water was examined [27F]. Experiments on a stratified layer of salt water under a layer of fresh water with heating from the side walls simulates roll-over which can occur in LNG containers [49F]. Numerical calculations and experiments show the transient convection when an initially stably-stratified horizontal layer is heated from below [69F].

Instabilities can develop in an initially thermally-stabilized plane layer when a DC voltage is applied across it [46F]. Pumping produced by traveling electrical waves superimposed on a dielectric fluid with a transverse temperature field has been studied using finite-element methods [42F]. Significant heat transfer enhancement is predicted when ions are created at an electrode by an electrochemical reaction in a fluid layer heated from below [10F].

Combined or mixed convection occurs when the driving force for flow is induced both by buoyancy and by some overall pressure difference which may have been provided by a pump or blower. An analysis of mixed convection in developing flow between parallel walls includes the influence of viscous dissipation [4F]. A numerical analysis of convection in a vertical channel predicts the heat transfer for both aiding and opposing flows [14F]. An analysis of mixed convection in a vertical channel with wavy walls indicates the potential of four different modes of flows [43F]. The relative importance of buoyancy and centrifugal forces in developing flow in a curved horizontal channel depends on the ratio of Dean number to Grashof number [73F]. Significant buoyancy effects can occur with forced flow through a heated spherical annulus at low Reynolds number [56F]. Flow through a reservoir of fluid used for energy storage is strongly influenced by buoyancy forces [12F]. For flow through a low-aspect-ratio channel filled with porous media, there is a considerable range of conditions under which the Nusselt number can be obtained from simple addition of forced and natural convection correlations [21F].

NATURAL CONVECTION—EXTERNAL FLOWS

An asymptotic solution of the Navier–Stokes and energy equations for the problem of free convection from a vertical finite plate is considered [20FF]. The structure of natural convection in flat, variously oriented layers of liquid and on a vertical wall is described [17FF]. Highest-order effects of Darcian free convection boundary-layer flow adjacent to a semi-infinite vertical flat plate with a power law variation of wall temperature were examined theoretically [5FF]. The fire plume along a vertical wall is analyzed using a laminar boundary-layer model, including finite-rate, gas-phase chemical kinetics [4FF]. Axisymmetric free convection flow of a viscous incompressible fluid above a horizontal plane surface is analyzed when the temperature of the plane surface oscillates about a nonzero mean [3FF]. Turbulent convective heat transfer, with appreciable buoyancy effects, over a heated or cooled horizontal flat plate is numerically analyzed by solving four equations for mean square temperature variance, its rate of destruction, turbulent kinetic energy and the rate of kinetic energy dissipation [6FF]. Approximate analytical solutions using a momentum integral method were used to study the effect of longitudinal oscillations on free convection from a horizontal plate [12FF]. Two-dimensional natural convection below an infinite strip and axisymmetric convection below a circular plate are calculated for a uniform surface temperature and a uniform surface heat flux for the special case of liquid metals [25FF]. The effectiveness of a stabilizing solute concentration gradient in delaying the onset of convection in a horizontal fluid layer subjected to transient cooling from the top was investigated [15FF].

A finite-difference numerical scheme was used to study combined free- and forced-convection boundary-layer flow in a porous medium near a vertical wall and the model results show that the inertial and viscous effects have a significant influence on the velocity profiles and heat transfer rate at the surface [23FF]. A description is presented of the heat transfer and fluid flow through a confined porous layer heated and cooled along one of the vertical side walls [22FF]. The boundary-layer solution is described for the problem of heat transfer along a vertical wall facing a porous medium, in the general case where the pore Reynolds number is not necessarily less than order one [2FF].

A comprehensive experimental study was performed to determine the natural convection heat transfer characteristics of a heated horizontal cylinder situated in a vertical channel in air [27FF]. Steady three-dimensional conjugate natural convection heat transfer from a horizontal isothermal cylinder with infinitely large transverse isothermal fins was studied numerically [29FF]. A study was conducted to determine the influence of fin length on steady, conjugate, natural convection heat transfer from an isothermal horizontal cylinder with one vertical longitudinal conducting plate fin [18FF]. The transition from conductive to convective heat transfer has been investigated for horizontal cylinders (platinum wires in various liquids), subjected to internal heat generation which increases linearly with time [10FF].

A formal, unified method is used to derive two sets of approximate equations governing the thermally-driven motion of strongly heated fluids [9FF]. A two-phase mathematical model is proposed for calculating the induced turbulent vertical flow and the temperature field in buoyant plumes driven by rising gas bubbles through a moderately stratified liquid environment [13FF]. An analysis is presented for mixed convection effects in a wall plume flow [16FF].

A solution is presented for self-similar mixed convection flow over a horizontal plate covering a wide range of conditions, beginning with purely natural convection and extending to forced convection separating flows [1FF]. A solution to the problem of mixed convection from an inclined vertical plate to a non-Newtonian fluid was presented [26FF]. Laminar mixed convection from a line thermal source imbedded at the leading edge of an adiabatic vertical surface is analytically investigated for the cases of buoyancy assisting and buoyancy opposing flow conditions [24FF]. An analysis is developed from mixed, forced and free convective combustion on a flat fuel surface of arbitrary inclination that makes use of the laminar boundary-layer approximation to describe the gas flow and of the flame-sheet approximation to describe the gas-phase reactions [19FF]. The desire to predict the convective heat loss from the solar receiver of a solar/electric power plant was the motivation for an experimental investigation of combined heat transfer from an isothermal vertical cylinder to a surrounding gas [7FF]. A finite-difference scheme is used to investigate mixed convection in flow through a finite rod array whose geometrical dimensions simulate those of a CANDU-type pressurized water reactor [8FF].

A mathematical formulation is presented for the transient development of the fluid-flow field and the temperature field in a liquid pool, generated by a spatially variable heat flux falling on an initially solid metal block [21FF]. The convective rates of heat transfer through inclined longitudinal slots are studied for the case where heat is transferred from a lower heated isothermal surface, through the slots, to an upper cooled isothermal surface [28FF]. Thermal instability and heat transfer by natural convection in an inclined rectangular water layer at low Rayleigh number have been studied using an interferometer [11FF]. The natural convection motion and heat transfer rate in an inclined rectangular air layer in which two opposing isothermal rigid walls were kept at different temperatures were investigated experimentally for various angles of inclination, aspect ratios and Rayleigh numbers [14FF]. Convective thermo-capillary instabilities in liquid bridges have been investigated [30FF].

CONVECTION FROM ROTATING SURFACES

The temperature distribution in a rotating cylinder is considered [16G]. Experiments are reported for a heated rotating cylinder in crossflow [10G]. Numerical solutions are presented for laminar convection between concentric and eccentric heated rotating cylinders [8G].

Heat transfer augmentation on a rotating cylinder by means of surface projections has been considered [12G, 14G]. A theoretical and experimental investigation of turbulent separated flows behind a rotating body is reported [9G]. Flow in circular tubes rotating about a parallel axis has been studied [7G]. Finite-difference solutions are presented in ref. [15G] for heat transfer in a metal-forming roll rotating at high speed. An integral analysis is given for the mixed convection from a rotating cone [6G].

Reference [13G] presents a numerical study of heat transfer in laminar flow through co-rotating parallel disks. Marangoni convection in a rotating fluid layer is considered in [5G]. Measurements are reported for the heat transfer coefficients in a rotating triangular duct [3G]. Finite-difference solutions are given for the flow between two rotating spheres [4G]. The rotating flow over an infinite porous disk is analyzed in [2G]. Heat transfer to rotating cryogens is considered in ref. [11G]. Reference [1G] deals with special wave effects in rotating media.

COMBINED HEAT AND MASS TRANSFER

For the purpose of this review the category of "combined heat and mass transfer" includes studies related to jet–mainstream interactions, such as film cooling and implingement heat transfer, as well as transpiration cooling and simultaneous heat and mass transfer in a number of applications including combustion.

Film cooling has been applied in many important systems, such as gas turbines, to protect surfaces exposed to high temperature gas flows. Experiments on the flow through an array of holes (shower head) near the leading edge of an air foil show the effect of injection (hole) angle and external flow pressure on the coefficient of discharge for the cooling holes [23H]. Injected jets separate from a convex wall at relatively high blowing rates, therefore, providing better cooling of the convex surface at moderate low and blowing rates than occurs on a flat surface [12H]. The characteristics of jets penetrating into a mainstream have been examined experimentally [25H]; these characteristics are important when trying to understand the different film cooling performance for different types of flow. The pressure drop across the large number of holes present in full surface film cooling, and the influence of interaction of heat transfer in the holes on film cooling performance have been studied [1H]. Experimental measurements using mass transfer to determine the effectiveness downstream of an injection slot show the influence of a downstream jet as could occur on a combustor lining [4H]. A model was set up to predict the heat transfer on a permeable surface with injection [18H]. Ablation of Teflon models in a Mach 5.74 tunnel with stagnation temperatures up to 1070° show the importance of the angle of attack on the shape changes in the model [3H].

Experiments on slot jet impingement cooling on the inside of turbine blades indicate a correlation of local Nusselt number with Reynolds number raised to the 0.6 power [16H]. Heat transfer from impinging jets to a flat plate on which a spike and external ring are present gave a much higher local heat transfer rate than on a surface without the protuberance, though the average heat transfer is not significantly changed [9H].

Another study of impingement heat transfer related to turbine blade cooling, indicates the effect crossflow air temperature has on impingement heat transfer as would occur at the mid-chord of a blade [6H]. The influence of external fluid temperature, different from that of the jet temperature on heat transfer has been studied from measurements with single circular jets [8H], and analysis [21H] and measurements [22H] on plane jets. Temperature profiles in jets mixing with a hot crossflow as occurs in a combustor, were studied experimentally and analytically [24H]. The impingement flow heat transfer results for different slot nozzle geometries can be correlated with an effective slot width proportional to the discharge coefficient of the nozzle [7H]. Heat transfer correlations were obtained from mass transfer measurements on a jet impinging on a cylinder, both with the jet in line with the axis of the cylinder [19H] and with it off-set from this axis [20H]. An analysis of the cooling effect of a jet impinging on a liquid surface first predicts the shape of the interface where the jet strikes the liquid [26H].

Experiments indicate the time to reach steady-state heat and mass transfer for natural convection surrounding a cooled horizontal tube in moist air [5H]. An analysis of a falling liquid film shows the influence of heat transfer on absorption; both the Sherwood and the Nusselt numbers reach asymptotic values a short distance from the start of the film [11H].

A special thermocouple probe has been used in a system similar to a thermosyphon to determine the natural convection during crystal growth [2H]. The effect of thermophoresis on particle flow deposition includes the influence of a transpiration cooled wall [10H]. The combined heat and mass transfer to particles in small Péclet number flow has been examined analytically to help understand chemical reaction on the surface of a particle [17H]. Experiments on the turbulent shear layer between adjacent flows of hydrogen and fluorine indicate a very large structure for the region of flow interaction that would influence combustion [15H].

The influence of porosity on the heat transfer from a permeable sphere to a low Reynolds number flow is relatively small if the Péclet number is large but is significant at small Péclet number [13H]. Analysis of the interaction of heat and mass transfer at an interface on which a soundwave is reflected includes a calculation of the time-averaged energy dissipation [14H].

BOILING

Pool boiling and nucleate boiling

A brief and humble personal recollection of the late Professor Nakayama's pioneering work in boiling heat transfer was published [44J], along with an English translation of his original paper of 1934 [45J] which established the fundamental characteristics of the boiling curve.

A kinetic theory approach was used to examine the theory of evaporation and condensation in the limit of continuum behavior [30J]. Mass fluxes predicted were in excess of the Hertz–Knudsen prediction, and the temperature profile appeared inverted from that expected, casting some doubt on the fundamental theory. Simple thermodynamic analysis of two hypothetical cycles was used to determine the relationships governing equilibrium radii of small vapor bubbles and liquid droplets [19J]. Stability and incipience theories for vapor nuclei were confirmed in experiments conducted with a specially prepared glass cavity and uniformly superheated liquid [15J]. New models of bubble growth rate and departure volume were developed for isolated nucleation sites and were shown to compare favorably with new and existing data [58J] while growth rates of groups of bubbles in a superheated liquid were analytically shown to be substantially less than those of isolated bubbles using an asymptotic matching of an inner region solution at the scale of bubble radius and an outer region solution at the scale of the bubble separation distance [8J].

An experimental and analytical investigation of nucleate pool boiling of water at 1 atm on a flat surface with varying angle relative to the horizontal demonstrated and postulated a model to explain that at low heat fluxes, greater angles (up to 175°, or very nearly facing directly down) produced higher heat transfer coefficients, while at higher heat fluxes the angle of inclination had little influence [42J]. Pulsed electrical heating was used to explore transient onset and development of boiling of liquid nitrogen on a horizontal wire and on a vertical plane film [18J]. The transient heating did not appear to induce premature transition to film boiling.

Enhancement of nucleate boiling was the topic of many of the papers reviewed. Enhancement of nucleate pool boiling by electrolytic production of hydrogen at the heat exchange surface was demonstrated [40J]. With simultaneous production of the gas bubbles, low wall superheats can produce large rates of heat transfer. The most prominent feature observed by the accompanying photographic studies was the reduction of the waiting period between bubble departure and the beginning of growth of the next bubble when hydrogen was also being produced at the surface. In a related article [41J] bubble frequency and bubble departure diameter were measured with this electrolytically-augmented boiling. The use of conical nucleation sites with reduced wettability was analytically explored [34J] and experiments were performed with the application of poorly wetting nucleation sites [36J]. Also reported were experiments designed to determine the optimum particle size for porous surfaces for nucleate boiling [16J]. An optimum particle size of 0.126 mm was suggested for use with refrigerant 113. Experiments with boiling of two binary mixtures on a commercially available enhanced boiling surface demonstrated that improvements in thermal performance, comparable to improvements in single component boiling, were achievable with mixture boiling but that activation superheats could be significantly higher than those predicted by a simple mixture interpolation [1J].

There were also several reports of mixture boiling on ordinary surfaces. Extensive experiments were conducted with pool boiling of binary mixtures of sulfur hexafluoride with three refrigerants over a wide range of heat flux densities, pressures and mixture concentrations [6J]. The reductions in heat transfer coefficients relative to those of pure substances were more pronounced at higher heat fluxes and at higher pressures. Concern with oil contamination within refrigeration systems led to experiments with nucleate pool boiling of mixtures of refrigerant 113 and oil [25J]. These experiments confirmed that substantial reductions in heat transfer coefficients result from increased concentrations of oil in such mixtures. A model incorporating the locally increased concentration of oil at the boundary of a growing bubble of refrigerant vapor was appended to the Forster–Zuber correlation, producing reasonable agreement with the experimental data. Oil–refrigerant mixtures were shown experimentally to exhibit dramatic increases in heat flux and wall superheat at critical heat flux as compared with the critical heat flux of pure refrigerant [24J]. Oily contaminants, especially those placed directly on the heating surface, were found to greatly reduce the effectiveness of nucleate pool boiling of water at atmospheric pressure [2J].

In other pool boiling studies, experimentation with varying arrangements of columns of heated and unheated horizontal finned tubes showed considerable enhancement of heat transfer coefficients by neighboring heated tubes at low heat fluxes, but performance approaching that of a single tube at high heat flux [67J]. Heat transfer characteristics of water boiling in a small thermosyphon were found to be comparable to those at 'small' surfaces in pool boiling, where 'small' surfaces have dimensions of the same order as the bubble break-off diameter [26J]. A simple model was developed to explain experimentally-determined variations in heat transfer coefficients and wall temperature during low heat flux heating of a liquid in a narrow rectangular channel with bubbles periodically injected into the channel [31J].

Flow boiling

Recognizing the utility of explicit functions for computer design and performance studies, the F and S functions of the Chen convective boiling correlation were presented in an analytical form [12J]. Local heat transfer was investigated for flow boiling of argon and of nitrogen in a horizontal tube [38J]. Heat transfer in co-current vertical two-phase flows was examined [48J]. Data of several investigations of two-phase heat transfer in two component vertical flow were correlated with a mixed flow Reynolds number determined as the sum of the liquid and gas Reynolds number determined as the sum of the liquid and gas Reynolds numbers [13J]. Another correlation based on momentum considerations was presented for bubbly and bubbly-slug flow in vertical tubes [11J].

An experimental study of flow boiling of refrigerant 22 inside tubes with a smooth wall, a smooth wall with a diametral fin, a microporous wall, and a smooth wall with a microporous diametral fin demonstrated that the microporous wall offered a marked improvement (up to a factor of 7.5) over the heat transfer coefficient of the smooth tube [23J]. In another augmentation study, a simple model was presented to estimate evaporation heat transfer in a channel filled with a highly conductive porous metal, and it was suggested that such a system would undergo no boiling crisis [37J].

Boiling in flow over rod bundles with blockages exhibited significant enhancement of heat transfer coefficients at certain locations downstream from the blockage [11J]. Correlations were developed from the experimental data for magnitudes and locations of the local enhancements. An experimental investigation of two-phase crossflow boiling heat transfer on a single horizontal cylinder showed large increases in heat transfer coefficients as compared with pool boiling [66J]. A correlation similar to the Chen correlation for convective boiling inside tubes was developed for this crossflow case and shown to fit reasonably well the data of the authors and that of two independent investigations.

Critical heat flux

An improved version of the critical heat flux correlation Katto proposed in 1978 has been developed to cover CHF in forced convective boiling in uniformly heated tubes, eliminating discontinuities between successive regimes [28J]. Additional experimentation expanded the data base for CHF in liquid helium to greater length/diameter ratios and demonstrated, contrary to earlier evidence at small length/diameter ratios, that helium also exhibits the 'high pressure character' in which the critical heat flux increases substantially with mass flux at large mass fluxes when vapor density is a large fraction of liquid density [29J]. two articles [60J, 61J] appear to be slightly different translations of the same Soviet source article, in which it is reported that no significant increase in wall temperature was evident at the transition from nucleate to film boiling of water in an 8-mm-diam. tube with pressures above 19 MPa (quality of 0.2), 17 MPa (saturated liquid) and 15 MPa (liquid subcooled by 25°C), suggesting transcritical heat fluxes with no tube damage. An experimental study of critical heat flux and post dryout heat transfer in helical coils was described [59J]. Results of local blockage experiments with water and sodium in model fuel subassemblies were summarized to estimate conditions of boiling and dryout applicable to liquid-metal fast breeder reactor (LMFBR) local fault assessment [69J].

An inclined plane surface used to investigate critical heat flux in flowing liquid films of water and refrigerant 113 produced nucleate boiling curves compatible with those of pool boiling rather than those of flow boiling, but demonstrated critical heat fluxes increasing with increased film velocity, both observations in agreement with other recent studies of liquid films. A model based on the competition between evaporation of a thin subfilm and replenishment of the film by droplets shed by the main film was shown to predict CHF for this system to within a constant [3J]. A correlation was presented for CHF in turbulent falling liquid films of water, ethanol and aqueous glycerol [20J]. Noting the difficulties of detecting dryout in a volumetrically-heated particle bed, an alternative experimental technique is suggested based on the additional time required for such a bed to reflood by gravity after the power input has been halted [56J].

Film boiling

Experiments with film boiling of water covering a pressure range of 20 kPa–2 MPa and heater diameters from 0.7 to 3.0 mm yielded: saturated film boiling heat transfer coefficients about 10% lower than predictions based on Bromley's expression; evidence that liquid/vapor velocity substantially contributes to subcooled film boiling; and evidence that the minimum heat flux and minimum temperature for film boiling are determined by different mechanisms above and below 1.1 MPa [53J]. Taylor instability appeared to govern at low pressure, while the heterogeneous spontaneous nucleation governed at higher pressures. Empirical equations were also given for interfacial wavelength, departing bubble diameter, and frequency. A theoretical model of minimum film boiling temperature and heat flux was proposed [54J] which included the effect of vapor film thickness. Predictions gave lower minimum heat fluxes and temperatures than the model of Berenson, particularly at high pressure. Experiments performed using a pulsed reactor allowed determination of transient subcooled film boiling heat transfer coefficients by way of inverse conduction calculations, showing good agreement with empirical correlations of earlier studies [46J]. A mathematical model of laminar film boiling for conditions with a large density change upon vaporization employed the effect of a pressure gradient caused by the increasing vapor thickness [65J]. The model predicted greater heat transfer coefficients at low flow velocities than the earlier model of Sparrow and Cess. A model based upon steady stagnation flow theory was developed for the case of film boiling on an oxidizing surface and shown to be consistent with available data of oxidation of zirconium particles [14J]. Analysis of flow film boiling over submerged bodies (spheres and cylinders) allowing a quadratic rather than a linear vapor velocity profile predicted thinner vapor layers and higher heat transfer coefficients, closer to those observed in available data [68J].

Droplet evaporation

Kinetic theory was applied to determine the direction of energy flow and mass flow to or from a spherical droplet surrounded by its own vapor, showing that under some circumstances (small Knudsen number and finite Reynolds number) the energy flow and mass flow may be in opposite directions [47J]. Analysis of vaporization of liquid droplets was used to show that the evaporation time of fuel sprays is proportional to the square of the initial mass mean diameter, and that as evaporation proceeds both the mean particle diameter and the Rosin–Rammler exponent characterizing the distribution of droplet sizes increase [9J]. A simple technique for evaluating evaporation time was presented, and it was shown that an optimal fuel droplet size distribution for combustion efficiency may not be optimal for ignition of the spray. A model of fuel droplet vaporization during the intake and compression strokes of a spark-ignition engine [35J] has demonstrated that the reduction in evaporation rate due to increasing pressure approximately offsets the increase in evaporation rate expected due to rising cylinder temperature. The model can also predict the maximum droplet size upon intake which will be completely vaporized at the end of the compression stroke. An analysis was performed on the behavior and evaporation of liquid droplets injected into the gas stream of a centrifugal compressor in the interest of approaching isothermal compression [50J]. Droplet size was determined to be the most crucial parameter.

Evaporation from freely falling droplets was also investigated [57J].

Using a laser shadowgraph technique, the interface stability of slowly evaporating liquid droplets on a vertical surface was explored [70J]. Dependent upon liquid properties, the interface behaviors fell into three categories: stable, substable and unstable, with the latter behavior exhibited by liquids with high dielectric constants.

A numerical model was developed to predict two-phase dispersed droplet flow heat transfer in a heated channel, extending previous analyses to include the effects of thermal radiation in systems at high pressure where the vapor was considered to be optically thick [10J]. An experimental investigation of heat transfer from a heated surface to uniformly sized impinging subcooled and nonwetting droplets [55J] illustrated little dependence of heat flux on wall temperature and droplet velocity. A simple model provided a plausible explanation for the lack of influence of wall temperature and good agreement with the data. A model was proposed for evaporation of a liquid droplet heated by a surrounding immiscible liquid [4J]. The bubble growth rate, Nusselt number, and time and height required for complete evaporation were shown to be dependent on Péclet and Jakob numbers, and good agreement was demonstrated with data of other investigators.

Reflooding, quenching and counterflow evaporation

Experiments performed with partially-blocked electrically-heated vertical rod bundles suggested that swelling (ballooning) of cladding does not severely impair the cooling of rod clusters during transient reflooding [22J]. Rewetting of a hot stainless-steel surface by refrigerant 113 was studied with varying liquid subcooling [62J]. A simple expression developed earlier from a one-dimensional wall conduction model reflected well the increase in rewet front velocity with increased subcooling, and heat fluxes in advance of the rewet front were shown to increase with subcooling. It was postulated in ref. [32J] that droplets in two size ranges emanate from the froth at a quench front, with the smaller droplets evaporating so rapidly that they vanish before reaching downstream measuring stations. The large number and rapid evaporation of these small droplets was proposed as the mechanism for the large rate of energy transfer immediately downstream of the quench front and, analogously, downstream of channel restrictions. The height of a two-phase region ahead of the quench front in a reflooding reactor core was measured in a thin 'slab' core [17J] and a predictive model was proposed, sensitive to transverse heat flux (power) profile and pressure-drop boundary conditions but insensitive to crossflow and to axial friction. An experimental investigation demonstrated the effective use of air–water mixture jets in quenching of machine parts [21J]. The technique allows the optimization of quenching rates as well as localized control of finished product properties.

The envelope theory, considering flooding to be the limiting condition for countercurrent flow, was compared with data for flows of condensing steam and water in inclined channels and shown to provide good agreement [33J]. While condensation had negligible effect on bottom flooding, an effective steam flow rate, recognizing the reduction of inlet steam flow by condensation, needs to be considered for top flooding. Liquid entry conditions were observed to have an important role. Experiments were described involving evaporation of water trickling down corrugated plates with an upward flowing air stream [7J].

Flashing

Linearized stability analysis was performed on the case of a rapidly evaporating (highly superheated) liquid surface [51J], suggesting strong instabilities with rapid growth rates. Experiments with sudden depressurization of refrigerant 11 demonstrated that the mass transfer rates during flashing were 10–12 times the rates due to evaporation and that liquid temperatures can fall well below the saturation temperature of the new low pressure [49J]. A combined experimental and analytical investigation of flashing of saturated water within a vessel showed strong dependence of the rate of vapor formation upon the initial level of water, the initial pressure and the diameter of the nozzle through which the vapor was allowed to escape the vessel [39J]. The time constant of the pressure response due to flashing was further related to the vessel's cross-sectional area. A model was suggested for non-equilibrium vapor generation for flashing two-phase flows, requiring *a priori* knowledge of the liquid superheat at the flashing inception point and using the bubble number density at inception as an experimentally-evaluated parameter [52J]. An experimental study of flash evaporation from turbulent water jets indicated that evaporation rates were essentially independent of the thickness of planar jets and that evaporation could be augmented through the use of screens or upward-directed vertical spouts [5J].

Other evaporation-related studies

A mechanistic model of liquid entrainment from a boiling or bubbling pool of liquid was developed [27J]. Good agreement was demonstrated with data from several independent investigations with air and water and with steam and water at various pressures. Experiments were performed to determine the heat transfer coefficient upon a vertical cylinder immersed in a liquid–liquid spray column in which discrete liquid droplets flow through another immiscible liquid [43J]. A simple physical model provided good agreement with the experimental results.

Advantages were demonstrated for the use of a two-phase cooling film for protecting a surface in a high-temperature air stream [64J], and a procedure was provided for calculating the efficiency of cooling of an adiabatic wall by such a film. An abstract of a special report [63J] outlined the use of natural convection cooling in storage of radioactive materials.

CONDENSATION

Dropwise condensation

Local heat transfer coefficients were experimentally determined on a condenser surface which was covered solely by active droplets (too small to be conduction-limited) [31JJ]. High-speed film records of droplet coalescence were used. Experiments were made on the effect of electroplating with silver to enhance dropwise condensation of steam—a significant enhancement was recorded [21JJ]. Silver provides a low-oxygen surface that absorbs trace organics from the surroundings promoting dropwise condensation. Measurements of heat transfer coefficient with dropwise condensation of steam on a vertical surface were made [11JJ]. Characteristics of droplet condensation were clarified. Heat transfer coefficients measured on the external, upper surface of a horizontal tube showed an influence of the frequency of the sweeping action of falling drops [10JJ]. This was dependent upon the tube diameter. Direct contact condensation was experimentally found to be conduction-limited [8JJ]. High heat transfer rates were attributed to deforming oscillations of the droplets due to surface tension—an analysis was presented to support this hypothesis.

A model was developed for droplet formation and growth in condensing binary mixtures—it was an extension of an unary condensation model [29JJ]. Predicted droplet size and density compared well with new experimental results, also presented. An analysis of binary nucleation and heterogeneous droplet growth was presented where a limit of unary condensation was shown [28JJ]. Droplets were shown to attain an equilibrium composition within 10^{-5} s after their metastable state. Comparisons were made with experiments.

Approximations used in the theory of dropwise condensation were assessed for use with mercury [20JJ]. Significant errors can arise when they are used. A numerical analysis was recommended. An analysis of liquid spray injection to a condensable environment showed that the observed reduction in spray angle (compared to injection into a noncondensable environment) is due to a reduced angle of the sheet region [14JJ]. This was confirmed experimentally for a laminar sheet flow. A model for condensation on a liquid droplet in its own vapor was presented [5JJ]. The vapor-phase boundary-layer equations were solved showing that the total rate of condensation varied inversely to the droplet radius. Laminar condensation on a spherical drop in forced flow was analyzed [3JJ]. Because of high radial condensation velocities, the drop was found to not be in the Stokes-flow regime, even though the drop translation velocity was low. Transient laminar condensation was next numerically investigated [4JJ].

Film condensation

Experiments and analysis were performed on the reflux condensation flow phenomena in a closed thermosyphon [6JJ]. The liquid film thickness is increased by vapor shear resulting in reduced heat transfer—Nusselt's solution cannot interpret the observed trends. An analysis of the effects of noncondensable gases on condensation in thermosyphons showed that the one-dimensional diffuse-front model is inappropriate [7JJ]. The importance of radial diffusion depends on the gas load and the ratio of the radial diffusion rate to the condensation rate. An important instability, condensation-induced water hammer, in inclined counter-current flow of steam and cold water was analyzed and a stability map was presented [13JJ]. Heat and mass transfer in turbulent tube flow with film condensation was studied [22JJ]. Condensation in tilted oval tubes was discussed [37JJ].

Condensation of binary mixtures with downward flow in tubes was experimentally investigated [19JJ]. Empirical equations were developed.

Condensation of steam on a subcooled water layer in co-current horizontal channel flow was experimentally investigated [17JJ]. Dependence of surface heat transfer rate on surface waviness was shown and data for a wavy surface was correlated. Experiments were made for downward-flowing vapor and vapor–gas mixtures over horizontal tubes [16JJ]. An approximate equation in boundary-layer form was shown to agree with the measurements. Similar experiments were made to investigate the effect of vapor velocity [15JJ]. Measured heat transfer rates were higher than predicted. It was felt that this is due to the onset of turbulence in the condensate film.

Measurements were made of vapor-phase temperature profiles and rates of condensation of binary vapor mixtures on a small, vertical flat-plate condenser [1JJ]. Data were correlated with a modified Nusselt model.

An analytical study of saturated turbulent filmwise condensation heat transfer was made of the vertical plate geometry [32JJ]. The velocity profile consisted of a laminar sublayer and a turbulent core using the 1/7 power law. Comparisons were made with previous data. Wavy filmwise condensation was analytically and experimentally investigated by assuming a sinewave film profile [27JJ]. Agreement with experiments was good when boundary conditions were properly given.

The effect of pressure gradient due to flow over a curved surface on film condensation was determined analytically [25JJ]. Solutions were not attainable for some locations in the downstream half of the tube. This is thought to indicate instability of the laminar condensate film which leads to enhanced heat transfer. Condensation on a laminar, falling film of immiscible liquid was numerically evaluated [23JJ]. Shorter film lengths were found to yield considerably higher heat transfer rates. Condensation of flowing vapor in a horizontal tube was numerically analyzed—the tube conduction resistance was included [9JJ]. Heat transfer characteristics resemble the uniform wall temperature problem for steam flow and the uniform wall temperature problem for refrigerant vapor flow. Turbulent film condensation in forced convection boundary-layer flow was investigated [33JJ].

Tests were performed to measure the critical conditions of water hammer initiation [2JJ]. The phenomenon is due to the collapse of a steam bubble in subcooled water flow. An analytical prediction model was presented. Arithmetical expressions were developed to describe the effect of excess vapor and the size of dead zones on single-pass gas-cooled condensers [26JJ]. These expressions allow the calculation of two-dimensional temperature and vapor-flow distributions within the condenser. Equations and guidelines were presented for the design of vertical condenser tubes—focus is on the effect of noncondensables [12JJ]. Results of experiments designed to determine the effect of oils on condensation in refrigeration systems were presented [34JJ]. An analysis was given for shell-and-tube condensers with shell-side enhancement using sharp fins [30JJ]. The fins allow a 20% reduction in heat transfer area under the conditions studied.

A survey of recent works studying the separate effects of condensate inundation and vapor shear in shell-side refrigeration condensers was presented [36JJ]. Appropriate correction factors for horizontal tube banks were sought. A survey giving the state-of-the-art of shell-side condensation in refrigeration condensers was made [35JJ]. Issues included vapor shear and inundation, enhanced tubes, noncondensables, oil and bundle geometry. A review of options available to improve heat transfer in film condensation of pure vapors was presented [24JJ]. The evolution of power condenser design and a discussion of present designs were given [18JJ]. Modeling of condenser shell-side heat transfer was discussed.

CHANGE OF PHASE

Freezing and melting

Theoretical and experimental studies of the phase-change process between solid and liquid or vapor phases have been reported for freezing within cavities and in duct flows, melting governed by natural convection in the melt and separation of components by selective freezing. Applications include continuous casting, frost formation in air flows and solid formation in pipe flows.

Basic work on the theory of the melting temperature and volume change vs pressure was developed for several pure metals [26JM–28JM]. The entropy minimum principle was used to develop governing equations for transient one-dimensional Stefan problems [22JM]. Results were obtained for a slab, cylinder and sphere.

Work on freezing included studies of crystal growth which can simulate the crystallization of metals [17JM, 1JM]. An implicit treatment of the temperature field with explicit boundary conditions was used to model the freezing process where more than one solid phase is possible [39JM, 40JM]. A finite-element method was applied to freezing in a corner by mapping the region onto a rectangular domain [19JM]. Another study used a similar method for solving a corner problem and included experimental data for comparison [23JM]. The effect of the boundary conditions on the convergence of finite-element solutions was addressed [41JM]. An experimental study was performed to measure the freezing time of a liquid contained within an inclined cylindrical cavity [18JM]. The inclination was found to have very little effect on the freezing time or heat extraction rate. Approximate solutions for the freezing time within a cube or a long cylinder of square cross section were provided [20JM].

Freezing problems involving a moving solid can be applied to continuous casting. The Cauchy boundary-value method and the product solution method were both used to obtain solutions for the interface of a melt being extruded horizontally between two insulated offset walls [37JM]. A similar study of a vertically extruded melt was made using the Cauchy boundary-value method [38JM]. A numerical solution was presented for the solidification of a steel casting in a rotating cylindrical mold in which the gravity force is negligible [21JM]. A closed-form solution was developed for the Stefan problem that exists when a hot wall moves over a semi-infinite solid [15JM]. Results for large Prandtl number reveal the role viscous heating plays in the melting process.

Solidification in channels has been studied both experimentally and theoretically. Experimental studies of ice formation between two horizontal plates have been made [34JM, 35JM]. The ice surface profile was found to depend on the flow Reynolds number and the instability caused by the ice layer. Numerical solutions were obtained for freezing inside a circular tube for laminar [5JM] and turbulent flow [32JM]. A finite-difference method was used to determine the surface contour and temperature distribution within the solid attached to a cooled plate immersed into a heated fluid [3JM].

A freezing process can be used to separate constituents of a fluid mixture. A one-dimensional Crank–Nicolson procedure was used to model the freezing out of a component from a bicomponent eutectic alloy [10JM]. The effects of various process parameters were examined. The freezing of a sodium chloride salt solution above a horizontal ice layer was studied experimentally with a simple analytical model used to obtain corresponding theoretical results [7JM].

Theoretical solutions were obtained for the freezing of water from a stream of humid air onto a flat plate [6JM]. Both laminar forced and natural convection situations were considered. Observations of frosting during early stages showed that the process begins with condensation of liquid water droplets which freeze and act as nuclei for the subsequent frost formation [33JM]. Freezing of supercooled water droplets suspended at the interface between two immiscible liquids was observed [36JM]. A similar study was performed to observe the freezing of water dispersed within an emulsion [29JM].

One-dimensional melting problems have been solved using a finite-element/Green's function method [25JM]. The inverse heat conduction problem with phase change has also been solved using a finite-element method [16JM]. An analytical procedure using the method of collocation has been used to study the phase change in a heat generating solid confined between two semi-infinite conducting walls [4JM]. The sublimation of a solid has been studied using a numerical approach with variable properties and an analytical solution using Green's function [11JM]. Good agreement between the two methods was obtained when using carbon.

Two-dimensional melting problems are often governed by the natural convection that occurs within the melt region. Melting adjacent to a vertical heated wall has been studied numerically [8JM, 24JM, 12JM]. An experimental study of melting and solidification in a two-dimensional rectangular cavity indicated that short fins were advantageous [13JM]. Temperature fluctuations were used to determine the melt structure and the natural convection flow regimes that existed in a melt of Lipowitz metal [9JM]. Melting of a solid contained within a horizontal cylinder was studied experimentally and theoretically when the solid is fixed [14JM] and when the solid is more dense than the melt and is allowed to sink to the bottom of the cavity [2JM]. Melting around a horizontal cylinder was studied numerically when the heated cylinder had a constant heat flux surface [30JM] and when the surface was maintained at a constant temperature [31JM].

RADIATION IN PARTICIPATING MEDIA AND SURFACE RADIATION

This review of radiation heat transfer literature is organized to first discuss works which treat general radiative heat transfer studies in various geometries. Works dealing with radiation coupled with other phenomenon such as conduction, convection or combustion, are discussed next. Literature on passive solar devices and solar radiation interactions with atmosphere is included. A number of papers on properties is also surveyed. They are roughly grouped into those dealing with radiative properties of thin films, small particles and how they scatter and participate in radiation transfer, gaseous absorption, and data concerning such materials as metals and insulations. A brief mention of instrumentations of interest is also included.

Analytical/numerical works outnumber the experimental work in radiation heat transfer in one-dimensional planar layers. The Galerkin method is used to determine radiation transfer in isotropically scattering [17K] and anisotropically scattering [16K] layers. Vertically inhomogeneous atmospheres with azimuthal dependences are treated by a multilayer discrete ordinate method [93K] and by the matrix operator theory which includes Mie scattering effects [33K]. Analyses of the dissipation of temperature perturbation in finite homogeneous [36K] and inhomogeneous [37K] atmospheres are presented. The question of uniqueness when considering reflection and transmission matrices of homogeneous, plane-parallel layer is considered [85K]. Analytical expressions for some of the integrals involving Legendre polynomials [15K] and Gaussian quadrature formulas for integrals with weight functions $\exp(-|x-t|)$ and $E_n(|x-t|)$ [86K] may be useful in future work. Experimental measurements of vertical and directional distributions of radiance in absorbing–scattering liquids [20K] are compared against discrete ordinate solutions which utilize experimentally-determined properties [46K].

Multidimensional radiative transfer in participating and nonparticipating media is the subject of many analytical and numerical studies. Two-dimensional rectangular enclosure geometry is considered in the following five references. [54K] studies the effect of surface radiant exchange and conduction on natural convection. Heat transfer and temperature profiles are presented for gray participating media at radiative equilibrium [110K]. Simple closed-form approximate expressions for a general multidimensional geometry is also presented and shown to be accurate for rectangular enclosures. Finite-element solutions for heat transfer and temperature distributions are presented for gray absorbing, emitting media where radiation is coupled with conduction [84K]. The S_n discrete ordinate method is presented for gray absorbing, emitting, isotropic scattering media and the results are shown to be very good compared to Hottle's zone and other methods [35K]. Numerical solution for two-dimensional, isotropically scattering, rectangular medium with diffuse incidence is presented [21K]. Finite-element solution for temperature profiles is presented for combined radiation, conduction and convection in a diverging/converging two-dimensional channel [19K]. A stochastic model is developed to handle general configurations with a finite number of isothermal, diffuse or specular, walls enclosing a nonparticipating medium [74K]. This model provides exact solutions if the appropriate view factors are known. [65K] presents view factors for a sphere coaxially placed within a cylinder. An approximate solution technique is developed for a general diffuse walled enclosure with nongray isothermal gases [75K]. In absorbing, emitting and isotropically scattering media, upper and lower limits, as well as explicit analytical expressions for geometric mean transmittance are given [109K].

Along with the references already cited [54K, 84K, 19K], the following consider radiation coupled with other modes of heat transfer. Combined conductive and radiative heat transfer is modeled for optically-thick, porous cordierite slabs and the results are compared with experiments [52K]. Transient coupled conduction and radiation heat transfer in an annular, absorbing–emitting medium is analyzed with a finite-difference technique [40K]. Experimental results are reported for heat transfer in a parallelogram enclosure, where surface radiation and conduction couple with natural convection [6K]. Radiation and convection are coupled in a thin shock layer: ref. [39K] presents an analytical solution for the flow around a body with a surface of zero total curvature, and ref. [94K] considers axisymmetric flow around a 35° sphere cone with chemical nonequilibrium effects included. For situations where the computation of complex flow fields, simultaneous with radiation, is needed, an adaptive-mesh radiation hydrodynamics is proposed [72K, 104K].

In a slightly different vein, thermal transport in spherical targets irradiated by laser beams [105K] and the temperature distribution on flat workpieces irradiated by Gaussian laser beams [87K] are investigated. The effect of radiation heat transfer is considered coupled with internal vibrational heating of polymers [42K], with internal heating in drying coated films [79K], and with endothermic gasification of a solid at depths [11K].

Interest in radiation coupled with combustion is shown in the works involving furnaces and other fundamental studies. Reference [60K] presents a review of models and experimental data for luminous and nonluminous flame radiation in turbine combustion chambers. Spectral normal directional emissivity data of a 16.5-kW test furnace shows up to 30% increase when the flame is loaded with carbon particles [53K]. Measurements and predictions of radiant heat fluxes and temperatures as functions of relative position to a turbulent methane diffusion flame are reported [51K]. On a more fundamental level, ref. [91K] considers the interaction between isotropically scattering particles and combustion gases, CO_2 or H_2O, in one-dimensional planar geometry. Reference [32K] reports on measurements of emission spectrum for carbon particles of 0.5 μm mean diameter which have been added to a 800–900 K nitrogen stream. Attention is also focused on the fly ash particulates: ref. [9K] reports scattering data, and ref. [96K] deals with measured total absorptivity. Study of laser vaporization of small soot particles, less than 100 nm in radius, reveals a decrease in size while the number density remains invariant [22K]. Soot diagnostics based on laser heating is reported sensitive in the 0.02–0.2 μm diameter range [71K].

Other combustion diagnostic techniques are considered. Spatially resolved measurements of OH concentrations using cross-beam saturated absorption spectroscopy are proposed [58K]. OH concentrations and temperature profiles in a premixed propane flame are obtained by laser deflection techniques [55K]. A number of papers report results from CARS technique: ref. [29K] reports data in augmented jet engine exhausts, [43K] on thermometry in full-rich combustion zones and [56K] from inside a firing internal combustion engine. Uncertainty propagation analysis in combustion diagnostics is discussed in connection with rocket and jet engine exhausts [62K]. Studies of the influence of particulate scattering on such plumes indicate a need for accurate particle size distribution information [76K, 77K].

Passive solar cooling for spacecraft motivates a theoretical study of a number of diffuse radiation shields [88K], as well as a study of those with effectiveness demonstrated by vacuum chamber experiments [7K]. Use of selectively infra-red emitting gases like ammonia, ethylene or ethylene oxide [63K], or coatings of MgO or LiF which have high solar reflectivity [8K] is considered.

A number of articles deal with the actual solar flux on earth and aerosols or participating gases in the atmosphere with which the radiation interacts. References [83K, 108K] report measured sky radiance in Kuwait and the tropics. Atmospheric aerosols have been studied: ref. [78K] reports on spectral extinction coefficient, [82K] on the scattering phase function of cirrus particles, and [34K] on the effect of humidity on aerosol scattering. Spectral absorption of atmospheric water vapor [41K] and NO_2 [69K] are reported. Transmittance band models of nitrous oxide [49K, 80K], SO_2 [81K] and methane [50K] in atmosphere are studied.

Partly due to continuing interest in radiation cells and also because of the importance of coatings in general, many works deal with radiative and optical properties of thin films. Studies that determine optical constants of thin films are reported in [4K, 10K, 103K, 70K]. Reference [10K] further notes that the film optical characteristics differ from the bulk, depending on the conditions during deposition. Reference [13K] discusses the determination of a thin-film absorption coefficient from CO_2 calorimeter data. Reference [26K] discusses the enhancement of solar absorption by having a film with rough top surface and a diffuse reflective bottom. Multilayer coatings for a high-power laser mirror optimized for 10.6 μm are described in [23K]. Specular reflectance of optical black coatings in the far infra-red (12–500 μm) is presented and modeled [92K]. Deposition of infra-red reflection coatings on glass is proposed to improve the efficiency of incandescent lights [106K], while antireflective coatings for glass will produce laser damage resistant coatings [107K].

Small particles and their interaction with radiation are the subject of the following papers. Work is presented to validate Mie emission theory for particles that are small compared to radiation wavelength [31K]. Effects of deep holes in the particle's scattering is studied by solving the Rayleigh–Gans–Debye and anomalous diffraction equations [59K]. It was found that the effect of relatively fine structure on total scattering by randomly oriented particles is small.

Light scattering of soil particles is calculated by modeling them as randomly oriented spheroids [45K]. Representations for the extinction and the Mueller matrices are given for a random distribution of nonspherical particles [47K]. Multiple scattering calculations are performed on an aerosol cloud [99K]. Effect of an intense pulsed light beam through absorbing water droplets is modeled [3K]. Scattering of sodium droplets in the cover gas of a sodium-cooled fast reactor is found to reduce radiant heat transfer by less than 10% [95K]. Reference [95K] also compares one-dimensional discrete ordinate method against other approximations. The effect of aerosol coagulation and deposition with time is added to the one-dimensional modeling for the radiation heat flux [100K, 102K]. Importance of anisotropic scattering in such considerations is emphasized [101K].

Information on the properties of nongray gases can be found. Total gas absorption models are proposed based on Elsasser band model and the effect of band contour and low-intensity lines [97K]. Total band absorptance estimates, including the nonoverlapping lines of vibration–rotation bands, are presented [89K, 90K]. Hottel's and Penner's rules for estimating the total absorptivity of homogeneous gases from total emissivity charts or expressions are generalized [30K]. Functional relationships between total and spectral molecular gas properties are considered in the derivation, and pressure scaling is also presented. Absorption band intensities are presented for propane at low temperatures [38K] and for CO_2 [25K]. Three overlapping CO_2 bands near 2.2 μm are analyzed by a nonlinear least-squares fitting procedure [1K]. Correction coefficients are given for the effect of dimerization on the infrared absorption of 6.3 μm water vapor band which is shown to be negligible [57K]. For computational ease, emissivity charts of CO_2 and H_2O have been converted to simple formulas [48K].

Radiation properties of liquids and solids are also studied. Total normal emissivity of liquid sodium is measured in an inert environment to be 0.045–0.057 for surface temperatures of 175–520°C [44K]. A method for determining the real part of the refractive index absorbing condensed media from reflection and transmission measurements is presented [61K]. Approximate formulas are given for the amplitude and the phase of specular reflectance at normal infra-red incidence for a conductor [73K]. Absorptivity of metals and their temperature dependence are considered [5K, 64K]. Optical constants for coal, char and limestone are obtained from combining reflection measurements from the particles dispersed in KBr tablets and the scattering calculations [12K]. Thermal radiative properties of ceramic materials are obtained from measurements made at 0.4–33.3 μm and 290–700 K [66K]. These properties are correlated with the wavelength, temperature, as well as other physical parameters. Results for the extinction coefficient and the first-order term in the scattering phase function are presented for high temperature insulation materials [14K]. Infra-red optical constants are presented for rare-earth doped crystals [111K], NH_3 ice [67K], magnesium fluoride [27K] and ice [98K].

Lastly, a brief review of articles on instrumentation follows. Construction and preliminary application of a thin path length cell, shorter than 10 μm, is reported [2K]. A near infrared remote sensing system for real time absorption measurements is described [18K]. PtSi Schottky infra-red CCD is considered for star detection from 1.2 to 2.5 μm [24K]. Optimization and theoretical ultimate NEP of bolometers are discussed [68K] and possible improvements suggested [28K].

NUMERICAL METHODS

Many problems in heat transfer are analyzed by the use of numerical methods. For the most part, the papers describing the application of a numerical technique to a particular problem are included in the appropriate application category. The papers mentioned in this section focus primarily on the numerical method rather than on the application used to illustrate it.

A combination of the boundary-element method and the analytic function method has been described [6N]. A solution method for the unsteady one-dimensional gas flow has been given in [16N]. An alternative practice to the use of wall functions in a turbulent flow is proposed [8N]; it involves the numerical solution of a simplified form of the turbulence model equations in the near-wall region. Reference [10N] describes multigrid methods for the diffusion equation; multigrid methods for flow are given in [7N]. A numerical procedure is presented in [2N] for compressible flow over a solid body. Some schemes for the flow solutions with nonstaggered grids are given in [12N]. Superposition technique is used to construct a three-dimensional numerical method [14N]. In ref. [5] suggestions are made for the calculation of the entrainment rate, initial values, and transverse velocities in the Patankar–Spalding method for two-dimensional boundary layers. A number of enhancements are described for the SIMPLE method for the calculation of recirculating fluid flow [15N].

The use of nonorthogonal coordinates for convection–diffusion problems is presented in [4N]. Reference [9N] applies the locally analytic differencing scheme to some convection–diffusion problems. The use of an adaptive collocation method for simultaneous heat and mass transfer with phase change is described in [1N]. The two-fluid model equations for boiling are solved by a simple and efficient scheme [3N]. A numerical method is proposed for two-dimensional phase change problems [11N]. A finite-difference method is employed for calculating laminar film boiling [13N].

TRANSPORT PROPERTIES

Research in this area is noteworthy for its development of methods and devices for measuring the thermal properties of materials. Classical transport properties, i.e. coefficients of diffusion, thermal conductivity and viscosity, are the focus of some efforts; in other instances the particular state of a material or its use in special circumstances attracts study.

The apparent density of fine, highly porous particles in a powder is measured using a novel mercury microvolumeter which gives rapid, accurate measure of small volumes of such materials [22P]. The cooling capacity of aqueous aquaplast, an East German produced, polymer-based fluid, is investigated by means of a prismatic heat-flux probe and found to be intermediate between water (high) and oil (low); results have application to the quenching of hot metal parts initially at a temperature ~800°C [21P]. For a vertical plate submerged in a high Prandtl number fluid, the transient natural convection resulting from the sudden generation of a uniform heat flux inside the plate is analyzed. Time-dependent expansion solutions are constructed for flows near surfaces with zero and finite thermal capacity [6P].

For binary mixtures of sulphur hexafluoride with noble gases, diffusion and thermal diffusion factors are measured and compared with theoretical values calculated by means of the Chapman–Enskog theory. Excellent agreement between experimental and theoretical thermal diffusion factors obtains for He–SF_6 and Ne–SF_6 systems, less so for Ar–SF_6 and Kr–SF_6 systems [24P]. Thermal conductivity of gas mixtures continues to be studied by Kestin and associates using a transient, hot-wire instrument [10P, 11P]. The first of these examines binary mixtures of He, Ne, and Ar with CO (at 27.5°C, pressure range 0.7–12 MPa) and uses viscosity data from earlier measurement on these mixtures for calculating contributions of internal degrees of freedom. Despite the essential sameness of the low-density viscosity of these mixtures with those of nitrogen, the thermal conductivity is different, pointing to a significant contribution from rotational degrees of freedom. The second work examines the CH_4–CO system in the same state region; despite this increase in the body of accurate data a predictive algorithm is not yet forthcoming.

Thermal properties for selected porous materials have been studied. An unsteady-state method was developed for determining the thermal diffusivity of a porous sphere. Using theoretical considerations to relate thermal diffusivity to porosity, experimental measurements on four metallic oxides (Cr_2O_3, CuO, Fe_2O_3, V_2O_5) gave results in good agreement with literature values [15P]. For solids with complex pores a model, developed from an analogous diffusion model, is described for predicting pore gas thermal conductivity to be used in conductivity correlations for such materials. The model accounts explicitly for both molecular and Knudsen transport mechanisms and complex pore systems [26P]. The thermal conductivity of the microporous particulate medium, moist silica gel, is studied experimentally to determine the influence of porosity, water content, total gas pressure and temperature by using the transient hot-strip method. The predictions of the effective thermal conductivity of beds of such materials by four simple models agree reasonably well with measurements [4P]. In order to model a packed bed with stagnant fluid ref. [12P] considers energy transport in a fluid-saturated porous medium formed by a cubic array of cylinders, with stagnant fluid. The generalized method allows the overall effective conductivity, volumetric specific energy capacity and effective thermal diffusivity to be derived with good results having only the properties of fluid and solid and void fraction as parameters.

A number of papers deal with techniques for measuring the thermal conductivity of systems. A compact apparatus operates on the linear heat-flow principle using bar-shaped samples held between a heat source and water-cooled sink. It is designed to cover the range 10–380 W m^{-1} K^{-1}, 50–500°C with a ±3.1% agreement of results with certified values. The transient hot-wire method is used for measuring the thermal conductivity of a system in which the wire separates the half spaces of homogeneous materials having different thermal conductivities and diffusion constants. The configuration permits the construction of a measuring probe which simplifies measurements and allows the consideration of anisotropic materials [20P]. The thermal conductivity of pyrotechnic compositions is successfully determined by applying a published method for estimating the thermal conductivity of powders using an electrically-heated copper probe embedded in the sample. The pyrotechnic systems are compositions of antimony and potassium permanganate at various fuel/oxidant ratios [1P]. Large effective thermal conductivities, between two fluid reservoirs maintained at different temperatures and connected to each other by a capillary bundle, are obtained hydrodynamically by oscillating the fluid in the capillaries at high frequency. The hydrodynamic theory developed attributes the enhanced heat conduction to radial heat transfer across very thin Stokes' secondary layers. Results with water show effective thermal diffusivities up to 17,900 times those in the absence of oscillations, exceeding the conductance rates obtained with heat pipes [13P].

The rotating disc viscometer, consisting of a thin copper disc enclosed in a copper cylindrical cavity and activated by two alternating magnetic fields of different strength, requires only a small fluid sample and yields accurate but not absolute measurements in the vicinity of the critical state of the fluid [5P].

In the area of radiation heat transfer properties two papers report results of interest. High temperature fibrous materials are considered in [16P] where an inverse methodology is developed for determining the thermophysical and optical properties for such absorbing, emitting and highly scattering substances. The model accounts for the optical effects: single scattering albedo extinction coefficient, back scattering fraction, index of refraction and the thermal properties: conductivity and specific heat. In instances where day-to-day experiments do not require a standard laboratory-calibrated tungsten strip lamp, ref. [19P] describes a less expensive, uncalibrated lamp–optical pyrometer method.

The influence of temperature-dependent physical properties on the heat transfer in the turbulent boundary layer for parallel flow over a flat plate is considered using a numerical method in order to account discretely for the influence of various properties [23P]. Results indicate that some published methods lead to considerable error. In a related study, ref. [25P] derives the dimensionless groups describing the influence of temperature dependent properties in heat transfer for flow over surfaces generally. For a viscoelastic fluid, ref. [14P] presents estimated eddy diffusivities of momentum and heat.

Efforts continue to obtain from kinetic gas theories improved correlations for predicting dilute gas viscosity and thermal conductivity. The acentric (shape) factor, dipole moment and association parameter are used in [7P] to obtain consistent correlations for 17 pure nonpolar gases and 13 pure polar gases: average accuracy for viscosity, 1.6%, for thermal conductivity, 1.38%. In the instance of gaseous nitrogen, and sulphur hexafluoride and mixtures of these gases [17P] reports calculated transport properties which are in good agreement with published values, experimental and calculated, except for a diffusion coefficient ratio. A separate study on the P–v–t behavior of sulphur hexafluoride in the gas–liquid critical region [3P] uses a combination of the Burnett and Isochoric methods to yield results accurate to better than 0.01% in pressure and 0.02% in density and 1 mK in temperature.

For solid systems ref. [18P] describes an accurate versatile system for measuring the linear thermal expansion coefficient. A laser interferometer and parallel spring strip supporting system provides accuracy and general purpose, yielding coefficients accurate to better than 3%.

A useful review article [2P] considers the three types of temperature sensors (resistance thermometers, thermistors and thermocouples), their characteristics and the design of circuitry to convert their outputs to a voltage signal, pointing out the use of a microcomputer as signal processing element to improve accuracy. An interesting examination of Newton's original work in defining a temperature scale, his use of fixed points and his law of cooling in the high temperature range, reconciles his results and conclusions with our current knowledge [9P].

HEAT TRANSFER APPLICATIONS

Heat pipes and heat exchangers

Research on various aspects of heat exchangers is impressive for the variety of circumstances investigated and the detailed examination of the various influences which can affect the transfer of heat. The most novel work [45Q] analyzes the simultaneous exchange of heat and water vapor in a crossflow-type total heat exchanger made of Japanese paper impregnated with a hygroscopic agent. Predictions and experiments for temperature and humidity efficiency show good agreement; the heat transfer rate is dominated by the air rather than the paper, for mass transfer the reverse is true. Disk- and doughnut-type heat exchangers for oil cooling are studied experimentally for various combinations of flow rates and clearances between baffle and shell [18Q]. Another experimental study [43Q] investigates the critical heat flux in helical coils with up and down flow of steam–water mixtures and finds striking differences from the vertical straight-tube arrangement.

Design considerations attract the attention of a number of workers. Two new compact heat exchangers specifically designed using the technique of 'local assumption' are studied and their predicted and measured duties found to agree [14Q]. Multiple parallel passages are used to cool a hot stream of a viscous polymer [24Q]; the analytical treatment of heat transfer and pressure drop leading to a unique exchanger design. For general heat exchanger design, ref. [50Q] introduces a new form of design chart to replace the five which currently exist in the literature; two exchanger configurations are presented (others to follow) with chart displaying both design and performance parameters. Reference [47Q] presents a numerical method for designing the entire tube-bundle heat exchanger using local heat, mass and momentum exchange information. The thermal design of a high-pressure compressor rotor for a turbojet engine uses a small amount of air from the secondary air system to vent the rotor cavities; an improvement in compression is achieved and the rapid thermal response of the rotor is better matched to the casing resulting in reduced clearances, higher compressor efficiencies and larger surge margins [19Q].

A series of analytical investigations using various techniques address a number of the chief concerns in general heat exchanger design. Using the decomposition strategy, ref. [26Q] examines the general problem of n_h hot streams and n_c cold streams with specified mass flows, fluid heat capacities and inlet–outlet target temperatures for the minimum number of heat exchanger units. Matrix formalism is applied to calculate the effectiveness of assemblies of heat exchangers for cases where the complete mixing condition for each fluid in inlet and outlet streams is relaxed [29Q]. The finite-difference method is used to predict exit-fluid temperature responses for a unit step increase in entrance temperature of either fluid [34Q]. A technique is presented for calculating thermophysical transients in fuel-element assemblies of a reactor cooled by dissociating N_2O_4 [16Q]. Test data and theoretical predictions show good agreement, confirming the validity of a modified selected point matching technique for testing compact heat exchanger surfaces [12Q].

Heat exchange in the presence of phase change engages the interest of [8Q] where the influence of heat and mass transfer resistances on the separation efficiency in molecular distillations is considered; ref. [17Q] has as its goal the development of specific equations for desuperheated design based on experimental measurements and [32Q] considers direct contact heat transfer in the course of motion by a vaporizing two-phase droplet.

Rotary heat exchange is the focus of a group of studies: ref. [9Q] considers numerically and analytically the influence of transient or nonuniform inlet temperature upon the temperature of the outlet stream for such exchangers; [3Q] considers the representation of regeneration fluid carry over from one stream to another due to the motion of the exchanger matrix. Reference [21Q] uses a finite-difference model of a counterflow rotary dehumidifier to determine the influence of the properties of dehumidifier performance. For fluidized bulk solids, ref. [52Q] uses experimental observations to aid the practitioner in laying out a direct-contact heater of rotary-tubes, tumble dryer or plate dryer type.

In the area of heat pipes, ref. [13Q] describes interesting test results for integral heat-pipe sandwich panels which combine the thermal efficiency of the former with the structural efficiency of honeycomb sandwich construction. Within the wick of a heat pipe ref. [38Q] measures the working-fluid distribution. For horizontal operation, the saturation temperature was found to be uniform in the adiabatic and cooling sections but dropped off sharply in the heating section. Dryout of the wick occurred at lower heat flux in the top-heated mode than in horizontal operation. Experiments and analysis assess the performance of a commercial heat pipe under operational conditions [37Q]. Fouling and scaling effects upon heat exchanger performance are a major concern in many applications. Reference [36Q] reviews generally the fouling process. A description of that process, deposition and removal would require an analytical fouling model. Design practice attempts to compensate for this lack of knowledge by overdimensioning of exchangers using estimated fouling factors (with fair success) and operation stresses continuous cleaning systems. An effective scheme for detecting fouling by means of an on-line monitor is described by [49Q] as a potentially useful diagnostic approach for discriminating between different types of deposits *in situ*. Using ring-type turbulence promoters, [15Q] shows that the maximum thickness of scale inside tubes is smaller than in smooth shell-and-tube heat exchanger tubes.

Heat transfer to banks and bundles of tubes is studied under various circumstances. As a first step to obtain basic data for heat transfer and flow around tubes in a staggered tube bank, measurements are obtained for a single tube in three or four staggered tubes in crossflow of air with constant heat flux [2Q]. Another experimental study shows a slight effect of angle of attack on the average heat transfer coefficient of staggered and in-line tube bundles through which water flows [55Q]; two staggered bundles of twisted oval tubes are studied experimentally for crossflow of air with average heat transfer coefficients 10% higher than a corresponding bundle of smooth circular tubes [44Q]. A related work studies average heat transfer coefficients and hydraulic drag of in-line and staggered tube bundles at various relative pitches [56Q]. To establish the suitability of the commonly used forced convection correlations in the instance of ceramic heat exchangers using SiC tubes, ref. [40Q] measures friction factor and heat transfer data, concluding that either the tube surfaces require smoothing or the heat transfer models need modifications.

Nonsteady effects on heat exchanger performance are reported by [39Q] where pulsatile flows enhance performance beyond the expected for curved tube flows; [48Q] considers analytically and experimentally the steady-state temperature responses of a one- or two-pass exchanger subject to sinusoidal flow rate changes of large magnitude; [31Q] associates the variation of local heat transfer coefficient over the tube perimeter in staggered and in-line configurations with the fluctuation of local air velocity during crossflow. Additional effects considered are: the influence on the performance of a tubular heat exchanger located downstream of a right-angle bend [41Q] and the dynamics of an independently heated heat exchanger with nonuniform axial distribution of the heat flux density [6Q].

The flow pattern in shell-and-tube heat exchangers is revealed in interesting photographs obtained by flow visualization using the oil-lampblack method [28Q]. Heat transfer in shell-and-tube heat exchangers with condensation on the shell side is studied [11Q] and reviewed [25Q]. A model is proposed that predicts the axial temperature distribution in a radiation recuperator based on radiation exchange between a combustion gas and the annular recuperator walls [51Q]. Conditions are determined under which heat exchanger assemblies are invarient to the interchange of the two fluids [30Q]. A simulation of the dynamic character of systems of heat exchangers is compared with experimental results [33Q].

Sponge- and filament-packed heat exchangers received consideration for the special purpose of cooling ^{3}He [5Q] and in longitudinal counter-flow of air under conditions of evaporative cooling of water in a film-type contact heat exchanger [27Q].

Economic and optimization considerations are integral features of operating heat exchangers. Various levels of optimization are considered in order to facilitate selection and promote economic design of heat exchanger equipment [22Q]. Heat transfer measurements were performed for in-line and staggered tube banks at various spacings, the optimium spacing being that which maximizes the heat transfer per unit of pumping power [1Q]. Using simplifying assumptions, ref. [20Q] gives concise expressions for calculating the dimensions of spiral heat exchangers with minimum annual cost of heating surface and pumping energy. The utility of static mixing devices is examined for use in tubular heat exchangers transferring heat to or from highly viscous liquids [10Q]. A thermodynamic efficiency based on the Second Law is defined for heat exchangers in terms of the mean temperature difference between two fluids exchanging heat and an environmental temperature and used to predict the effect of heat exchanger parameter changes upon efficiency of energy use [53Q].

The use of fins to improve the performance of heat exchangers attracts the interest of a number of investigators. For a two-row tube and plate fin heat exchanger the overall heat transfer coefficient measurements, together with published results for one-row measurements, permits local mass transfer coefficients to be transferred to local heat transfer coefficients [35Q]. To assess the optimal condition for finned heat exchanger ducts, ref. [23Q] considers the case for laminar flow and proposes the optimal configuration as that which provides maximum heat transfer per unit cost of finned duct. Heat transfer and pressure drop measurements are measured for finned tube banks arranged parallel and at specified angles to the flow direction [4Q]. To improve the performance of compact heat exchangers inclined, louvered fins are proposed [46Q]; their likely effect is predicted by means of a simple theoretical model and experimentally studied to determine the specific fin configuration giving optimum heat transfer and pumping loss characteristics. The heat transfer in a crossflow shell-and-tube heat exchanger is augmented by the use of wall radiation [54Q] in both shell and tube sides, with maximum overall coefficients of heat transfer as much as 80% larger than those for the same circumstances but with radiation absent. A simple, accurate (although approximate) calculation procedure adapts the findings to practical use. For designer–practitioners, ref. [42Q] reviews a number of the more noteworthy topical developments in the improvement of heat transfer by convection, in evaporation and condensation.

Using beds of glass beads and sand to represent a fluidized bed, ref. [7Q] measures the heat transfer between such media and horizontal, square, in-line tube bundles of various pitch. Results are compared with those predicted by five models in the literature.

General

Prediction methods for the performance of film-cooled gas turbine blades were compared [8S]. Cascade experiments [11S] determined aerodynamic losses connected with film cooling and optimized [29S] turbine blades with respect to heat transfer. The effect of vibration on the film cooling effectiveness and losses was measured in vane cascades [16S]. End wall flow and heat transfer were determined from flow visualization [9S] and measurements [36S]. An experimental investigation considered gas turbine disk cooling [17S] and the heat flux distribution in a turbine stage [6S, 7S].

A numerical study determined the transient temperature field in a furnace and compared the results with measured values [14S]. Cold model tests of the flow and heat transfer in furnaces of powdered coal boilers were compared with full-scale furnace tests [1S].

A parametric study analyzes heat transfer during a loss of coolant accident to check the validity and limits of the computer model [24S].

Heat transfer was measured in stirred multiphase systems [18S] including suspensions [27S] of micromolecular substances. Heat transfer data were also obtained experimentally for heating helical coils [13S], for vertical tubes with film evaporation [33S], and for tubes in bubble column reactors [34S]. Dissolved gas was found [15S] to have a negative effect on the critical heat flux in forced flow heat exchangers. The analysis and design of viscous flow coolers was discussed in [23S].

The state of the art in heat and mass transfer was reported for open cycle OTEC systems [4S].

Experiments and analysis using microcomputers consider insulation of attics [28S] and basements [19S, 35S].

A number of papers consider heat transfer in tribology, either for bearings [10S, 20S, 21S] or for sliding contacts [3S].

Numerical calculations consider heat transfer in strip rolling [32S] and in forging [5S].

A number of papers deal with drying of grains [25S, 26S, 31S], of coal [22S], and of wood [2S], as well as of optically semitransparent materials [12S], and in vibro-fluidized beds [30S].

Solar energy

The transient collector performance test method defined in the British Standards Institute Draft for Development DD77: 1982 is shown to be effective in determining the steady-state characteristics of flat-plate collectors from measurements taken under variable conditions [8T]. Flat-plate collectors having copper-tube/copper-sheet and copper-tube/aluminium-sheet absorber plates have been analyzed, fabricated and field tested [24T]. An analytical model was developed to extend the current techniques used in the prediction of the performance of nonmetallic flat-plate solar collectors [18T]. The transient periodic characteristics of flat-plate solar collectors, subjected to solar flux that fluctuates were evaluated experimentally and analytically [21T, 22T]. A comparison of single-equation methods to approximate the top loss coefficient for flat-plate solar collectors is made with the value obtained using the iterative solution of the energy balance equations [9T]. A simple analysis has been developed to predict the transient response of a tubular solar energy collector [1T]. The efficiencies of arrays of evacuated tubular collectors with diffuse reflectors have been determined experimentally using a calorimetric technique, and theoretically using a Monte Carlo ray tracing technique [6T].

The performance of a solar pond as a source of thermal energy has been modeled [20T]. The growth of a nonconvective zone by natural diffusion as a function of time from an initial two-layer configuration in a salt gradient solar pond was analyzed for two limiting cases: (i) complete mixing in the top layer and (ii) no mixing in the top layer [12T]. Transmission spectra and extinction coefficients for different salt solutions have been measured and the effect of pond transparency on the performance of a district solar pond is discussed [15T]. A numerical simulation of ground heat loss from a solar pond shows good agreement with the results obtained from pond measurements [11T].

A mathematical model gives the temperature distribution and the efficiency as functions of the geometrical parameters of a honeycomb structure collector which can be used for space heating in a passive solar system [10T]. The question of designing a nonhomogenous wall to optimize the 'thermal flywheel effect' is considered [7T]. Free convection turbulent heat transfer within the parallel plate channel of a Trombe wall has been studied [4T].

Measurements indicate that natural convection is not a major contributor to the destratification process in a rock bed and that designers of solar systems can safely arrange their ducting for either normal- or reverse-charging, selecting whichever is more convenient [23T]. A method is described of simulating the performance of a solar heating system which can be incorporated into a microcomputer-based system design and sizing procedure [17T]. Important parameters influencing the performance of devices for solar water heating and distillation were analyzed and discussed [5T]. Drying operations under humidistat and temperature control with and without a solar collector were simulated [19T].

The Gaussian Thermal Flux model is a fast thermal radiation submodel which operates with minimal input and predicts flux on sloped surfaces for both clear and cloudy days [13T]. The flux model was tested by sensitivity analysis and compared with observed data and other existing emperical models [14T]. The radiation to and from clear skies is an important solar energy topic. A discussion is presented of the equivalent radiative sky temperature [3T]. A new algorithm has been developed for calculating the thermal radiant temperature of the sky [16T]. In a related paper, the emissivity of clear skies is characterized [2T].

Plasma heat transfer

Plasma heat transfer and related applications are of continuing interest.

Parametric studies of thermal r.f. plasmas show (for argon and nitrogen at $p = 1$ atm) that the flow and temperature fields in the core region, as well as the heat flux to the wall of the plasma confinement tube, are considerably altered by changes in the torch operating conditions [24U]. Modeling of a free-burning, high-intensity arc at elevated pressures (>1 atm) shows that the arc contracts as the pressure increases and, as a consequence, the current density, the enthalpy flux and the voltage drop increase also [10U]. Comparisons between theoretical and experimental voltage–current characteristics of ablation-stabilized arcs confined in cylindrical tubes show good agreement [17U]. Nonequilibrium modeling of wall-stabilized AC arcs at low currents indicates that nonequilibrium effects are important near zero current [18U].

Studies of temperature and flow fields of a free-burning arc deflected by a transverse magnetic field indicate that the induced mass flow through the arc cools the arc and flattens its temperature field [7U]. Pressure and heat flux measurements of a thermal argon plasma flow confined in a water-cooled tube are reported. Axial distributions are in fair agreement with analytical predictions [15U]. Numerical results of simulating a thermal plasma flow in a cooled tube are reported [14U]. Experimental studies of the thermal boundary layer in dual-flow plasmas (dual flow orifice nozzle interrupter arrangement) are in reasonable agreement with theory [22U]. Firing of a high-energy plasma jet igniter reveals turbulent structures similar to turbulent puffs. Measurements of the growth rate of these features together with those of their impulse and thermal energy confirm this similarity [32U]. Analytical results based on an optically-thick model for radiative and collisional effects in nonequilibrium argon plasma flows in a circular tube are in reasonable agreement with experiments, indicating the importance of self-absorption effects (29U].

Investigations of the vapor flow patterns in free-burning, high-current arcs indicate two flow patterns depending on the electrode arrangement. Radiation losses exceed 84% of the total energy dissipation in the vapor dominant arc [38U]. Studies of the vapor diffusion from a copper anode in a nitrogen arc indicate diffusion speeds between 10 and 20 m s^{-1} [27U]. High radiation efficiency in high-pressure sodium discharges under controlled vapor conditions is favored by high input power and a mercury-rich amalgam [33U].

Experiments for synthetic gas production from peat using a steam plasma reveal a carbon conversion of 89% and a hydrogen-to-carbon monoxide ratio of 1.8 in the product gas [30U]. Results of thermal decomposition measurements of CO_2 in an argon plasma jet allow an analytical description of this process [11U]. Attempts to reduce TiO_2 by thermal plasma treatment indicate that, at best, 10% (by weight) of TiO_2 can be reduced to TiO by a carbo-thermic reaction [5U].

Coalesced multiple-arc discharges can be used for producing larger and more uniform volumes of ionized gas which is important for heating of gases and for plasma processing of materials [9U]. A 100 kWe magnetoplasmadynamic (MPD) thruster system may be applicable to a wide variety of future space emissions. Roughly 10% of the total electric power delivered to the thruster is converted into heat in the electrodes [28U]. Five optical fibers are heated simultaneously by a 50-Hz AC discharge for fusion mass-splicing of fibers [31U].

Radiation emitted by an SF_6 arc in the range 4000 $< \lambda <$ 6000 Å is due to radiative recombination of S^+. The values obtained for the Biberman factor are in good agreement with theoretical predictions [13U]. Non-LTE diagnostics of an argon arc shows that LTE is obtained in a 4-mm-diam. arc at atmospheric pressure for electron densities $n_e > 6 \times 10^6$ cm^{-3}. For $n_e < 6 \times 10^{16}$ there is an increasing underpopulation of excited levels as the arc current decreases [25U]. A new two-channel technique for determining electron densities in plasmas from Stark broadening is described and its utility is demonstrated with a laser-produced sodium plasma [3U]. Spectrometric measurements in free-burning argon arcs at $p = 1$ atm seem to indicate that there are departures from Local Thermodynamic Equilibrium (LTE) and deficiencies in the theory describing continuum emission [8U].

Total heat transfer calculations are presented for spherical and cylindrical probes in collisionless plasma flows [4U]. Results of an analysis for the plasma flow around blunt-body electrostatic probes exposed to a flowing argon plasma (arc jet) indicate that the electron temperature at the probe surface may be as much as 30% lower than the freestream electron temperature [2U].

A special arc arrangement has been developed for measuring the thermal conductivity of Cl_2 and O_2 in the dissociation region ($T \leqslant 6000$ K) using optical interferometry (20U, 21U]. Discrepancies between analytical predictions of the thermal conductivity of hydrogen for $T > 4500$ K and experimental results derived from arc experiments are attributed to strong deviations from LTE [26U]. Calculated thermodynamic and transport properties of plasmas produced by the ablation of Teflon, alumina, perspex, and PVC in high current arc switches are presented for temperatures from 5000 to 30,000 K [16U]. Even traces of metallic vapors may exert a strong influence on the properties and the behavior of thermal plasmas and on the associated heat transfer to injected particulate matter during thermal plasma processing [23U]. Calculations of thermodynamic and transport properties of a typical arc furnace plasma show that dissociation of molecular species has a strong effect on the specific heat and on the thermal conductivity of the mixture and the electrical conductivity is strongly affected by metallic vapors from the molten pool and slag cover [34U].

A simplified analytical model for an anchored cathode root in a DC mercury-vapor arc is based on the assumption that both electric current and heat pass through the solid metal anchor rather than through the thin mercury film which wets the solid anchor [19U]. Surface roughness and surface temperature have little effect on the movement of cathode spots in vacuum arcs which is important for establishing cathode heating models [12U]. Studies of the electrode erosion phenomena in high-energy pulsed discharges reveal that a large amount of the erosion is in the form of solid and molten material removed parallel to the electrode surface and from the edge of the macroscopic craters found on the cathode [6U].

The SF_6 spark develops through two different glow phases where the first stage is a low-current (~ 10 mA) phase followed by a second phase in which gas heating leads to dissociation of SF_6 in times of the order of 100 μs with a transition to a higher current (~ 1 A) glow phase [37U]. Studies of microwave absorption and plasma heating due to microwave breakdown in the atmosphere indicate that the microwave field strength in the ionization regions is attenuated to the breakdown value at steady state, and the resulting electron temperature is approx. 2 eV, independent of the incident microwave flux [36U].

MHD free convection flow about a semi-infinite plate has been investigated for the case of uniform heat flux to the plate [35U]. Investigations of magnetoconvection in a rotating fluid between walls of very low thermal conductivity show that in contrast to fluids under the same conditions but with walls of different thermal conductivity, the fluid in the present case is always thermally unstable for any Taylor and Chandrasekhar numbers [1U].

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