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HEAT TRANSFER—A REVIEW OF 1979 LITERATURE

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INTRODUCTION

THIS review surveys results that have been published in various fields of heat transfer during 1979. As in the past, the number of papers published during that period was such that only a selection can be included in this review. A more complete listing of papers is available in the Heat Transfer Bibliographies published periodically in this journal.

The Fourteenth AIAA Thermophysics Conference was held 4–6 June 1979 at Orlando, Florida. Twelve sessions dealt with subjects like radiation, thermal protection systems, thermophysics, heat pipes, contact resistance, thermal control, entry environment and technology, nonintrusive diagnostics, computing technology and thermophysical analysis. Papers presented may be obtained from the American Institute of Aeronautics and Astronautics.

The Eighteenth National Heat Transfer Conference organized jointly by ASME and AIChE was held 6–8 August 1979 at San Diego, California. An invited paper by Kenneth J. Bell treated design techniques for shell and tube exchangers. The Max Jakob Memorial Award was given to Niichi Nishiwaki, the Donald O. Kern Award to Kenneth J. Bell and a Conference Award Certificate to Joseph S. W. Chi for the best paper presented at the Seventeenth National Heat Transfer Conference. Thirty-six sessions were devoted to process heat transfer, solidification and melting, heat transfer in heat generating fluids and turbulent flows, radiation and process heat transfer, rotating flows, heat-transfer enhancement, interfacial transport, boiling, contact heat transfer, natural convection, waste heat recovery, solar energy, heat exchangers for fluidized beds, heat transfer in catalytic combustion, in porous media and packed beds, and in thermal systems. An open forum at which short presentations can be given has become a standing feature of this conference. Newcomers to the field or those who want to refresh their knowledge of heat transfer can participate in a Short Course Program of the ASME with courses in augmentation of heat transfer, heat transfer in fires, and numerical solution of heat transfer and fluid flow. The AIChE organized its Today Series Courses on practical heat transfer, in shell and tube heat exchangers, solar energy applications, fluidized bed heat transfer and applications in combustion. Papers are available through ASME and AIChE in bound volumes.

A Short Course on Fluid Mechanics Measurements, held 10–13 September 1979 at the University of Minnesota, brought together experts to present, after an introduction to physical laws and measurement, lectures on flow visualization, hot wire and hot film anemometry, laser velocimetry, measurements in two-phase flow, in non-Newtonian fluids, volume flow measurements, and computers in flow measurements. The lectures will be published in book form by Hemisphere Publishing Corporation, Washington, D.C.

The 1979 Seminar of the International Centre for Heat and Mass Transfer was devoted to heat and mass transfer in metallurgical systems and was held 3–7 September 1979 at Dubrovnik, Yugoslavia. Ten sessions covered heat transfer in blast furnaces, in the processing of iron and steel, during crystallization, in welding and cutting, in turbines and combustors, diffusion treatment, and corrosion. The proceedings will be published by Hemisphere Publishing Corporation.

The First National Conference on Numerical Methods in Heat Transfer convened 24–26 September at College Park, Maryland. Twenty-two lectures discussed finite difference and element methods.

The Winter Annual Meeting of the American Society of Mechanical Engineers was held 2–7 December 1979 at New York and included eighteen sessions on heat transfer. S. Levy discussed, as luncheon speaker, the importance of fundamentals and real time in heat transfer analysis. The Heat Transfer Memorial Award was presented to Arthur E. Bergles. Reprints of the papers presented at the meeting are available at ASME Headquarters in New York and many of them will be published in the *Journal of Heat Transfer*.

The Fourth International Symposium of Plasma Chemistry was held in Zurich, Switzerland from 27 August to 1 September 1979 and attracted more than 250 participants from 20 countries. Discussions of heat transfer in thermal plasmas generated by means of arcs or rf discharges were augmented by specific applications in the area of extractive metallurgy, the production and purification of solar grade silicon, the gasification and desulphurization of coal, and plasma spheroidization. One session was devoted to diagnostic techniques including LDA and thermogravimetric methods.

Trends and developments in heat-transfer research during 1979 are characterized by the following highlights: As in recent years, the conduction literature continues to be dominated by phase change and related moving boundary problems. Other active areas of heat conduction include solution methodologies (both analytical and numerical), the inverse problem, composite and anisotropic materials, variable properties, thermal contact, and fins. In general, this was an active year for heat conduction. The number of conduction papers in this year's review is the largest ever.

Recent studies of heat transfer in channel flows reflected a strong interest in complex flow configurations, fluids of various properties, and oscillating and pulsating flows. Significant attention was also given to the nature of the thermal entry region and specific techniques for augmenting heat transfer.

Boundary layer literature covers turbulent jets, flow over a cylinder, and laminar and turbulent boundary layers on walls. Effects of curvature and of Coriolis forces have been given attention. Numerical solutions as well as experimental work have been reported.

Literature on transfer mechanisms is largely concerned with mathematical models for turbulence. New models are proposed, existing ones are discussed and applied to new situations. Some new experimental data on the structure of turbulence have been reported.

A considerable number of papers considered natural convection in an enclosure with two vertical walls of different temperatures. This geometry was selected as a test case for an evaluation of various numerical schemes. Natural convection in porous media and in plumes also found interest.

Experimental and analytical results were published for heat transfer in rotating flows considering geometries like disks, rotating freely or in enclosures, tubes, and nozzles. Combined heat and mass transfer papers included chemical reaction, thermal diffusion, change of phase, and presence of particulates. Film and transpiration cooling found attention in a number of papers.

Boiling is a process which still needs clarification for a complete understanding. Accordingly, a large number of papers treat fundamental and practical aspects of boiling with strong participation by authors from the U.S.S.R. Film evaporators have found special attention.

Literature devoted to the study of heat transfer during condensation included investigation into the problem of film condensation, the effect of material properties on dropwise condensation, and condensation in two-phase and multi-component flows. A significant number of papers were concerned with the problem of heat transfer during melting and freezing. Melting topics included: the melting of ice and paraffins, the influence of natural convection on the melting process, and the determination of melting fronts and local heat-transfer coefficients during the melting process. The problems of freezing in a low gravity environment, salt rejection during the freezing process of saline solutions, and the effect of natural convection on freezing were topics included in the literature of heat transfer during freezing.

Some experimental results on radiation properties have been reported. The analysis of radiative energy transfer considered various geometries and surface properties and included phase change.

Laser Doppler anemometer and hot-wire hot-film techniques continue to be developed for a large variety of heat transfer subject areas including the study of the flow distributions in two-phase processes, arrays of heat exchanger tubes, subsonic and supersonic free jets, mixing layers, and engines. The development of specialized techniques and equipment for the experimental investigation of heat transfer in two-phase flows and plasmas was reported.

Heat transfer characteristics of a number of geometries of heat-transfer surfaces have been reported, and improved calculation methods for heat exchangers account for leakage, bypass, and irregular flow pattern. Heat pipes are treated in a number of papers, including characteristics of wicks and degradation.

The largest number of papers on solar energy continues to deal with the experimental and analytical evaluation of the performance of active solar collectors. The studies are distributed approximately equally between flat-plate and concentrating collectors. There was an increase in the number of papers describing the thermal performance of passive solar heating systems and components.

In 1979, there has been a substantial increase in research activities in plasma heat transfer associated with new developments in arc circuit interruption and in plasma processing.

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 that category.

Conduction, A
Channel flow, B
Boundary layer and external flows, C
Flow with separated regions, D
Transfer mechanisms, E
Natural convection, F
Convection from rotating surfaces, G
Combined heat and mass transfer H,
Change of phase, J
Radiation
  Radiation in participating media, K
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Heat-transfer applications
  Heat exchangers and heat pipes, Q
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Plasma heat transfer, U

CONDUCTION

As in recent years, the conduction literature continues to be dominated by phase change and related moving boundary problems. Other active areas of heat conduction include solution methodologies (both analytical and numerical), the inverse problem, composite and anisotropic materials, variable properties, thermal contact, and fins.

Experimental studies of solid–liquid phase change indicate that the commonly accepted dominance of heat conduction may not be valid. Experiments have demonstrated that freezing in the presence of a superheated liquid can be drastically slowed and ultimately terminated by natural convection in the liquid [72A]. Photographs of melting about a horizontal heated cylinder affirmed the dominant effects of natural convection [1A]. Heat-transfer measurements for melting about horizontal heated cylinders showed that the convection-dominated heat-transfer coefficients for a multi-tube array are similar in magnitude to those for a single tube [57A]. Another experimental study of melting about horizontal cylinders affirms the importance of natural convection [10A].

The classical Stefan problem, when converted from a constant surface temperature boundary condition to a constant heat flux boundary condition, is characterized by an interface position which is described by a power series in $t^{1/2}$ (t = time) [75A]. Another form of solution for the constant flux boundary condition leads to a first-order ordinary differential equation relating the interface position with the time [19A]. Exact solutions of freezing or melting of a polymorphous material in a semi-infinite region are expressed in polynomials and functions in the error integral family [76A]. A similar form of solution was employed for the Neumann problem subjected to convection at the heating (or cooling) surface [77A]. For phase change, the effects of density change are usually omitted in classical solutions. By an appropriate transformation of the space and time variables and the material constants, it is possible to transform a variable density solidification problem into one with equal densities in both phases [78A]. The periodic variation of the surface temperature bounding a phase change medium gives rise to multiple phase boundaries [14A].

Solidification due to the presence of a line sink of heat has been solved exactly, subject to a model characterizing the distribution of the solid fraction within the two-phase zone which results from an extended freezing range between the solidus and liquidus temperatures [48A]. Short time solutions for cylindrical freezing were obtained via Boley's embedding technique, with the governing partial differential equations being converted to integro-differential equations and then solved by series expansion [27A]. A perturbation method has been employed to analyze the problem of freezing of a biological tissue when a predetermined constant cooling rate is imposed on its outer surface [61A]. A problem of growth and decay of the frozen layer that forms in forced flow on a finite non-melting wall served as the vehicle for the presentation of a refined version of the heat balance integral method [20A, 21A]. Another refinement of the heat balance integral method was used to solve for solidification about a cooled cylinder [12A].

To provide design data for phase-change thermal storage systems, information on total melt time and average surface heat flux was determined for a phase-change material subject to a constant temperature at its boundary [69A]. In a related paper, a simple relation is presented between the wall temperature of a semi-infinite phase-change material and the time when this temperature is attained during a melting process with a convective boundary condition [70A]. Convective heating prior to melting and subsequent melting of a semi-infinite solid were both analyzed by employing Biot's variational principle [54A]. Teflon ablation has been modeled as a two-layer problem, one layer being a gel and the other a solid [6A]. Phase change driven by radiation and aerodynamic heating can be reduced to an initial value problem by use of Biot's variational method [84A].

The isotherm migration method has been rephrased in an implicit format and applied to a two-dimensional Stefan problem [18A]. A numerical scheme for conduction phase change treats each phase alternately [60A]. An application of the method of fractional steps and of the method of lines to the numerical solution of two-dimensional Stefan-type problems is described [44A]. To reduce the computational effort needed to solve multi-dimensional phase change problems, a similarity rule has been evolved which applies to problems in which sensible heat contributions are much smaller than latent heat contributions and where the heat flux distribution on the surface of the phase change substance is more or less uniform [65A]. Monte Carlo simulation was employed as a tool to investigate the sensitivity of a Stefan moving boundary problem to the uncertainty associated with the input information [45A].

Various topics in steady conduction, encompassing both new solutions and methodologies, have been treated. For steady heat-conduction problems with oblique-derivative boundary conditions, the use of Green's functions reduces the boundary value problem to equivalent integral equations [55A]. Another approach is to decompose the second-order partial differential equations into first-order systems [56A]. Steady conduction in the circle-in-square geometry was solved by a conformal mapping method [36A]. Conformal mapping also proved useful in solving a steady conduction problem in a slab with segments of convection and insulation on one face and uniform temperature on the other [49A]. An isoperimetric lower bound was obtained for the steady heat flow across a strip-like region when the temperature is constant on one boundary and satisfies a convection condition on the other [2A]. Numerical solutions gave results for the temperature distribution along the exposed surface of a convectively cooled wall whose rear side is heated by a periodic array of groove-embedded heating elements [71A]. To limit the heat transfer into a volume from the boundary surface, a control array of heat sources or sinks may be positioned near the surface [52A]. A thermocouple model was employed to derive an estimate of temperature measurement errors associated with the presence of the thermocouple [62A]. Study of a steady state heat-conduction problem involving a thin disk affixed to a convectively cooled solid plate was motivated by the measurement of heat fluxes from convectively cooled surfaces by thermopile heat flux gages [83A].

Several papers dealt with thermal contact. Calculations based on existing models have provided values of thermal contact conductance as a function of applied load, both for elastic and plastic modes of surface deformation [16A]. The macroscopic constriction experienced by a heat flux in passing between stainless steel and copper surfaces can be alleviated by insertion of a copper gauze [4A]. Theory, corroborated by experiments, shows that the contact resistance is reduced when the slipping speed between two solids in friction is increased [81A]. Predicted conductances of stacks of laminations corresponding to a wide range of contact pressures and with various interstitial fluids agreed well with measurements involving disks of stainless steel, brass, and transformer core steel [80A]. In the theory of contact conductances, a single contact on the surface of a semi-infinite body is frequently used as a building block for the case of surfaces which have many contacting points. The validity of this approach has been recently re-examined [11A].

Fins continue to draw some attention. Fin-to-fin, fin-to-base, and fin-to-environment radiant interactions were accounted in determining the efficiency of a convecting–radiating fin array subject to a timewise-periodic base surface temperature [24A]. Computer-aided extension of the regular perturbation series for a radiating fin yielded highly accurate results [8A]. Solutions based on the heat balance integral have shown that the efficiency of a triangular fin departs from that of the traditional one-dimensional model as the apex angle increases [15A]. A generalized approach to the one-dimensional modeling of fins enabled identification of the proper dimensionless parameters which govern the problem [58A].

Interest persists in composite and anisotropic materials. The governing differential equation for three-dimensional steady conduction in solid and hollow cylinders of general anisotropic media can be reduced to Kummer's equation by use of the Fourier transform and a change of variables [17A]. It was also shown that certain heat-conduction problems for anisotropic media can be transformed into corresponding problems for isotropic media [51A]. Some solutions for transient head conduction in cylinders with three-dimensional anisotropy have been presented [50A]. For steady state heat transfer in a heat generating composite solid composed of two materials, Green's functions were used to convert the boundary value problem into a Fredholm integral equation of the second kind [25A]. The model for heat conduction in which a two-phase composite material is regarded as spheres of the dispersed phase situated in a lattice of the continuous phase has been solved for the case where the spheres are infinitely conducting and nearly touching [74A]. In order to explore longitudinal heat propagation in matrix-filler bilaminates, it is necessary to augment it into a trilaminate [28A].

Transient conduction papers have dealt with a variety of topics. The linear one-dimensional diffusion equation may be solved by the method of variation of parameters, which yields a solution in the form of an infinite series of products of eigenfunctions and time-varying coefficients [13A]. A collection of Green's functions has been assembled for transient conduction problems whose boundaries vary linearly with time [29A]. A variational method for the solution of the transient heat-transfer problem in nuclear reactor elements was used to analyze the consequences of a shutdown of the reactor [37A]. A solution for transient heat conduction in the ground due to buried radioactive nuclear waste takes account of orthotropic thermal conductivity and of the time-varying nature of the heat generation rate due to radioactive decay [82A]. Analytical solutions are given for transient heat transfer between a semi-infinite solid and a perfect conductor with internal heat generation, taking into account a thermal contact resistance at the interface [46A].

There was special emphasis on transients in the presence of variable thermal conductivity. The orthogonal collocation method, which involves the approximation of the spatial derivative term by an orthogonal polynomial of the Legendre type, was shown to be a highly effective tool for solving transient problems having variable conductivity [39A]. Existing variable property solutions for transient conduction in a semi-infinite solid have been supplemented by a new set of solutions obtained via perturbation methods [64A]. A perturbation method was also used to solve transient heat-conduction problems with spatially random thermal conductivity [3A]. For a semi-infinite solid with periodically time-varying surface temperature, variable thermal conductivity causes the propagation of a given harmonic to be affected by the amplitude and phase of the other harmonics [68A]. For a thermal conductivity which varies as a non-negative power of the temperature, a perturbation method yielded a similarity solution of the transient heat-conduction equation [9A].

The inverse problem of transient conduction was treated in several papers. Timewise temperature information at an interior point of a solid cylinder can be used to determine temperatures at other interior points for given boundary conditions [31A]. A method for determining the transient surface temperature of a solid when the temperature variation at an interior point is known employs approximate iterative techniques suitable for the solution of one-dimensional transient thermal conduction problems in homogeneous or composite solids [7A]. It was also found necessary to use an iterative technique to solve the inverse problem of heat conduction when variations of thermal conductivity are considered [41A]. Through examples it was demonstrated that a finite-element method can be effectively used to treat the inverse heat-conduction problem [35A]. A method was presented that enables the quantitative evaluation of the resolving power and accuracy of surface temperature predictions generated from inaccurate and discrete interior measurements [30A]. The key ingredient in an approximate method for solving both the direct and inverse variable property heat-conduction problems is to replace the original non-linear partial differential equation with a succession of equivalent linear ones in some optimum fashion [32A].

In addition to numerical work already cited in earlier paragraphs, other numerically oriented papers will now be reported. Use of the finite element method for transient thermal problems can lead to the anomalous result that, even in the absence of local sources of heat, temperatures near suddenly cooled boundaries show an initial increase [23A]. A numerical method for transient heat conduction with variable conductivity uses a finite element discretization in space and the Crank–Nicolson discretization in time [47A]. To extend the applicability of finite difference techniques for the solution of transient heat-conduction problems, a finite difference approximation was formulated in generalized, nonorthogonal coordinates [59A]. Two new methods of introducing nonlinear derivative boundary conditions for ADI methods have been developed [73A]. An explicit numerical method for solving transient combined heat-conduction and convection problems uses the DuFort–Frankel method for the conduction equations and the fully implicit scheme for the convection equations [26A]. A five-parameter family of two-level 10-point difference approximations to the two-dimensional heat operator is given and its characteristics explored [33A]. The orthogonal collocation method proved to be highly effective for solving transient conduction in a composite slab with variable thermal conductivity [38A].

There are interesting control and statistical aspects of heat conduction. There are many industrial processes in which it is necessary to control the temperature distribution in a given material. The resulting optimal control problem was reformulated as a mathematical programming problem by discretizing the space coordinate by finite elements while the Runge–Kutta method was utilized for time integrations [43A]. The heating of a slab by the ambient temperature is formulated as an optimal control problem with the view of attaining a certain temperature level in the slab while keeping the ambient temperature as low as possible [42A]. In certain industrial processes concerned with the manufacture of steel, it is necessary to determine control temperatures to be applied at a number of time steps to the surface of the steel ingot to induce a specific temperature variation within the ingot. The resulting dynamic control problem was converted to one of static optimization and then solved using a partial quadratic interpolation technique [22A]. Parameters in the heat-conduction equation should be estimated by Aitken's method when the errors are correlated [63A].

In a highly mathematical treatment, the hyperbolic form of the heat equation for pure heat conduction is generalized to combined heat- and mass-transfer processes [66A]. Nonlinear thermoelasticity theory allows heat to travel with finite wavespeed [40A].

Some heat-conduction-related papers that were published in *Heat Transfer, Soviet Research* include: moving boundary problems [34A, 53A], inverse problem of transient heat conduction [5A, 79A], and analytical techniques in nonlinear transient heat conduction [67A].

CHANNEL FLOW

Recent studies of heat transfer in channel flows reflect a strong interest in complex flow configurations, fluids of various properties, and oscillating and pulsating flows. The nature of the thermal entry region concerned many authors, and others addressed specific techniques for augmenting heat transfer.

The problem of convective heat transfer in tubes once again was an area of active research. A numerical analysis for laminar heat transfer in a pipe with convective and radiant wall fluxes indicated that axial conduction is strongly altered by the parameters responsible for the convection and radiation, and increases as the heat flux at the wall is decreased [4B]. Numerical calculations performed for the problem of hydrodynamic steady flow in a round tube for varying Reynolds numbers and for different laws governing wall temperature demonstrated the influence of longitudinal diffusion on *Nu* [14B]. Assuming hydrodynamically stabilized flow and constant fluid properties, solutions were obtained for convective heat transfer in tubes for conditions when heating varies arbitrarily over the perimeter and length at the same time [13B]. Local and average heat-transfer characteristics were studied for turbulent air flow in an asymmetrically heated tube. The results show a strong interaction between circumferential wall conduction and fluid convection under non-uniform heating and a significant effect of wall conduction at low *Re* [20B]. A finite difference procedure was used to predict turbulent flow and heat transfer in horizontal, inclined, and vertical pipes when influenced by buoyancy. Results were presented for the velocity and temperature fields, and the associated flow resistance and heat-transfer coefficients agreed well with experimental results [1B]. Using an eddy conductivity model, an analytical solution to the problem of turbulent heat transfer in pipes with internal heat generation and insulated walls provided results which agreed closely with the available data over a wide range of *Pr* [25B]. An experimental investigation of the turbulent structure of velocity and temperature fields made in fully developed pipe flow of air demonstrated that in the turbulent part of the wall region, the axial heat flux, as well as the intensity of the velocity and temperature fluctuations, reach their maximum. In the turbulent core, the intensity of the fluctuations decreased, indicating the velocity and temperature fields are approaching isotropy [17B]. An experimental investigation was performed on the basis of a vortex statistical model of turbulence to determine losses of energy in channels. Losses were shown to include the disruption of the small scale part of turbulent structure which is brought about by viscous forces in tiny vortices, and a semi-empirical relationship was presented for these losses [46B].

Research was also actively pursued for channel flows of different geometries. An analytical study of momentum and heat transfer for turbulent forced convection in rectangular channels demonstrated that only a single secondary current occurs in the trapezoidal symmetry element of the rectangular duct. This study accounted for secondary anisotropic turbulent transport properties and turbulence-induced secondary flow, and included the effects of peripheral wall conduction as well as radiation [26B]. An experimental study of the heat-transfer rate from a plate to accelerating streams of air, water, and transformer oil in rectangular channels determined that the heat-transfer rate deviated from that corresponding to a turbulent mechanism. This deviation was shown to occur gradually for favorable pressure gradients, and the magnitude of the deviation was shown to be a function of velocity and geometry [35B]. Double beam interferometry was used to determine the development of local mass-transfer boundary layers for laminar flow in a rectangular channel. The application of an overall mass balance permitted the distinction between different concentration contours associated with optically indistinguishable interference fringes. A Pohlhausen function was found best to describe the concentration profiles in the boundary layers under steady laminar forced convection [23B]. An experimental study showed that tubes of eliptical cross-section give higher laminar flow heat-transfer coefficients than those of circular cross-section but with an accompanying penalty in pressure drop. These experiments were performed for constant wall temperature conditions and over various aspect ratios [31B]. A numerical analysis was developed to predict friction factors and heat-transfer coefficients in a pipe of irregular cross-section. Finite element solutions substantially agreed with experimental results and showed that *Nu* varies with *Ra* and the cable configuration [6B]. Using a simplified differential energy transport equation for turbulent flow, a new method was presented for the transformation of turbulent Stanton numbers measured in an annular channel geometry. The thermal performances of rough surfaces were evaluated for a single rod and when extended to a rod bundle, agreed well with experimental results [18B]. An experimental study was performed of local heat transfer from the inner and outer tubes of an annulus under various heating conditions. For the case of two sided heating and moderate heating rates, the effect of the variability of physical properties on heat transfer for varying *Re*, diameter ratio, length to diameter ratio, and heat flux ratio, is virtually independent of the boundary conditions at the other tube, and reduces to the identical effect described for one sided heating [28B, 29B].

The effects of curvature on fluid flow and heat transfer in channel flows with different boundary conditions was also addressed. A numerical study of fully developed viscous flow and heat transfer in curved semicircular sectors was studied for thermal boundary conditions of (i) axially uniform heat flux with uniform peripheral temperatures and (ii) axially uniform heat flux with mixed conditions at the periphery. The fractional increase in heat- or mass-transfer coefficients to the fractional increase in friction factor for curved and straight semi-circular ducts was greater than unity for all cases studied and increased with both Dean and *Pr* numbers [22B]. The effect of curvature on fluid flow and heat transfer in a tube with axial uniform heat flux and peripherally uniform wall temperature was analyzed numerically, and demonstrated that secondary flow circulations become more complex as the Dean number increases. The Nusselt number was shown to increase with increasing Prandtl and Dean numbers, and a method was provided to find the optimum convergence parameter which substantially reduced computational time [36B]. An experimental investigation was also performed for the hydrodynamics and heat transfer in a curved channel with a rectangular cross-section which accounted for not only curvature but also the shape factor of the cross-section [11B].

Many authors addressed the problem of characterizing momentum and heat transfer in the entrance region of channel flows. An experimental study of the velocity and temperature profiles in a high temperature (up to 3000 K) air stream in the initial section of a tube with turbulent flow showed that the velocity and temperature of the air stream at the tube axis remained practically constant for ratios of length to diameter which were less than or equal to 10 [19B]. A step-by-step analysis of developing laminar flow in straight ducts of arbitrary but constant shape was performed by modifying a finite element code for non-linear heat conduction [10B]. In a related paper, a finite element technique was used to solve velocity and heat-transfer characteristics in the thermal entrance region of hydrodynamically developed laminar duct flows of arbitrary but constant cross-section [41B]. A numerical simulation of asymmetrically heated pipe flows suggested that flows require 150 diameters from the start of heating to reach full development. In this study, particular attention was given to the anisotropy of the turbulent thermal diffusivities [7B]. By considering the droplet heat-transfer contribution as a distributed heat sink, convective heat transfer of laminar droplet flow was calculated numerically for the thermal entry region of circular tubes with constant wall temperature [44B]. From an analytical investigation conducted for the random entrance region heat transfer of a fluid in a parallel plate channel with boundary conditions of randomly varying temperature oscillations, it was concluded that as convective heat-transfer increases, the variance increases and the thermal field must be described by both the mean and the variance [5B].

Several papers were published dealing with channel flows of fluids with variable properties. The results obtained from an implicit finite difference scheme used to determine a solution for heat transfer in laminar non-Newtonian Couette flow with a pressure gradient were in good agreement with a previously obtained semi-analytical solution [21B]. Experimental results were performed for mass transfer in a pipe for an aqueous 4% NaCl solution under Newtonian and non-Newtonian conditions. For the non-Newtonian flows, there was a significant reduction in mass transfer [42B]. An adaptation of the Lévêque solution for the case of mass transfer from a flowing fluid to the core of an annulus in the fully developed streamline flow of a non-Newtonian fluid was compared to experimentally-determined mass-transfer coefficients as measured using an electrochemical technique. The results showed that mass transfer in non-Newtonian fluids following the power law model can be well represented by a modified version of the simplified Lévêque solution [37B]. The average rate of heat transfered to the channel wall when a hot incompressible third order fluid in rectilinear motion flows (i) between two parallel plates and (ii) in a circular tube was investigated. Heat-transfer coefficients were evaluated for several values of a non-Newtonian parameter, and were enhanced for those fluids which exhibited large strain rate gradients in the region of the channel wall [12B]. A numerical and experimental investigation of friction and heat-transfer parameters for turbulent flow of helium–argon mixtures (Pr = 0.4–0.49) was performed in smooth electrically heated vertical circular tubes and demonstrated that popular existing correlations developed using gases with Prandtl numbers on the order of 0.7 overpredict observed Nusselt numbers. By comparing numerical calculations and measured constant property Nusselt numbers, Prandtl numbers were determined in the wall region which were valid for conditions where properties varied greatly [33B]. Asymptotic methods were used to analyze channel flow with temperature dependent viscosity and internal viscous dissipation. Flow was shown to evolve from a Poiseuille flow with a uniform temperature distribution to a plug flow with hot boundary layers. An asymptotic solution was obtained for the transition flow region, and an explicit expression was derived for the pressure gradient in terms of the local downstream coordinate [30B]. The Lévêque solution for the high Graetz number (thermal entry) flow of a Newtonian fluid in a circular pipe or rectangular channel was extended to derive higher order terms in the power series expansion of temperature for the flow of a power law fluid [38B]. Laser anemometry and thermocouple measurements were used to compare turbulent heat transfer in dilute solutions of polymers in a rectangular channel with theoretical results. The results demonstrated that velocity and temperature distributions are steeper for the dilute solutions than they would have been for the universal curve for water [34B]. Turbulent heat transfer in dilute polymer solutions was also studied to evaluate the effect and extent of drag reduction and deterioration of heat transfer [45B]. A numerical calculation was performed for turbulent flow in rough pipes using a mixing length model in the turbulent core and a roughness drag element coefficient and sublayer Stanton number to characterize heat transfer to the wall. Variable property effects were more pronounced for rough pipes as compared with flow in smooth pipes, and terms on the order of the roughness height divided by pipe radius were shown to be significant [43B].

Momentum and heat transfer in complex channel geometries was also an area of strong interest. Experiments performed to study how fluid withdrawal at a branch point in a tube affects the turbulent heat-transfer characteristics of the main line flow downstream of the branch showed an augmentation of the circumferential Nusselt number of the main line flow. The augmentation increased at any fixed Reynolds number when the ratio of withdrawn flow to main line flow was increased [40B]. Experimentally determined heat-transfer coefficients for turbulent air flow in a circular tube were studied for flow conditions situated downstream of a mixing tree. Results demonstrated that mixing and turning of the flow gives rise to significant augmentation of heat-transfer coefficients as compared with those of a conventional thermal entrance region, and that the thermal entrance length is also substantially elongated [39B]. A finite difference numerical analysis was used to investigate laminar transport phenomena in constricted parallel ducts with fully developed flow and temperature profiles. Thermal conditions of uniform temperature and uniform heat flux were used to determine thermal and hydrodynamic effects at both the entrance and exit of the constricted flow geometry [3B]. Experimental measurements of developing and fully developed heat-transfer coefficients along a periodically interrupted surface affirmed the preclusion of the obtainment of hydrodynamic and thermal development. The presence of the interruptions served to augment the heat-transfer coefficient, and in the case of fully developed flow, the coefficients are on the order of twice those of a conventional duct flow [8B]. The use of circumferential grooves was shown to be of advantage in an electrochemical study which compared the enhancement of mass-transfer coefficients for horizontal conduits with various grooved surfaces [24B]. Heat transfer and turbulent flow in internally finned tubes and annuli were analyzed using a mixing length model, and in general, the fins were found to be as effective a heat-transfer surface as the wall (per unit area). The local heat-transfer coefficient exhibited a substantial variation along the fin height and lesser, more gradual, variation on the tube wall or annulus [32B]. The electrochemical analog technique was used to measure mass and heat-transfer distributions in pipes roughened with small square ribs. The mass-transfer distributions were less uniform at high Reynolds numbers and were virtually independent of the Schmidt number over a wide range. An analytical and numerical study of augmented heat transfer and thermal homogeneity was performed by comparing motionless mixing by both flow division and inversion. Nearly optimal results were achieved with a practical no pressure drop two channel partial flow invertor with an increase of 20–30% in Nusselt number [27B].

Oscillating and pulsating flows in channels were also studied. Using the electrolytic method, the transition from laminar to turbulent flow was measured for oscillating and pulsating flow in a pipe. The critical Reynolds number was shown to be dependent on the amplitude and frequency of the oscillation, and for pulsating flows, there was an additional dependence on the superimposed stationary flow [16B]. The density wave stability boundary and the growth of temperature perturbations were experimentally observed for supercritical helium in a long heated channel of high aspect ratio. During the density wave oscillation, the channel exit temperature and inlet mass flow were observed to be in phase and the oscillation period was close to twice the fluid transit time [9B]. Mass transfer in a hydraulic fully developed flow within a tube with steady pulsating and oscillating flows was studied using the electrolytic method. The mass transfer was increased by up to five times the value of the steady flow condition, and experimental records showed details of turbulence, flow separation, and backflow [15B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Boundary-layer research continues to focus on experimental and theoretical studies of laminar and turbulent flows on rough and smooth, flat and curved surfaces. Jet impingement on surfaces and flow around cylinders and spheres are also topics of considerable interest.

The Prandtl number dependence of the Nusselt number for the laminar flat-plate boundary layer has been expressed by a correlation that is very accurate over a very large range of the Prandtl number [35C]. In a similar study, approximate formulas of very high accuracy have been obtained for heat transfer from a flat-plate boundary layer with blowing or suction [36C]; the formulas cover almost the entire range of the Prandtl number and the blowing/suction parameter. It is shown that the average Nusselt numbers for external flows for uniform wall temperature and uniform heat flux turn out to be almost equal if they are appropriately defined [32C]. Analytical solutions have been presented for the two-dimensional boundary layer flow of a power-law non-Newtonian fluid [28C].

A number of calculation methods have been presented for laminar and turbulent boundary layers. A simple analytical method is proposed for heat transfer in turbulent boundary layer with a hydrodynamic starting length [21C]. Turbulent boundary layer with separation has been calculated by an integral method [1C]. Calculations have been presented for the thermal layer developing within a velocity boundary layer with a step change in wall temperature [9C]. A modified integral method is described for boundary layers with prescribed surface heat flux [43C]. Approximate methods are developed for calculating the properties of laminar boundary layer of heated water [22C].

In other boundary layer studies, the growth of the two-dimensional mixing layer from a turbulent and nonturbulent boundary layer is investigated [8C]. A study is made of the turbulent boundary layer with large freestream to wall temperature ratio [6C]. Influence of the external flow on heat transfer has been determined for the boundary layer of a continuously moving plate [20C]. The hydromagnetic flow and heat transfer over a stretching sheet is the subject of one investigation [13C].

An analysis has been presented for the growth of an ice layer on an isothermal plate in a forced-convection parallel flow. Results for laminar flow are compared with experimental measurements [23C]. Also, experiments for transition and turbulent flow are reported for the ice layer [24C]. The stabilizing and destabilizing effects of Coriolis force on two-dimensional laminar and turbulent boundary layers have been investigated [27C]. Heat transfer from a rough plate has been measured in the flow of air and transformer oil [17C]; further data on the drag and heat transfer on a rough wall have been presented in [16C].

A number of studies have been conducted to determine the effect of surface curvature on boundary layer heat transfer. Heat-transfer measurements for turbulent boundary layers on convex and concave isothermal surfaces have been presented [30C]; the concave surface is found to transfer more heat than a flat surface, while a convex surface transfers less. Detailed measurements have been reported for the turbulent boundary layer on a flat surface downstream of short convex or concave regions [41C]. The heat transfer in the boundary layer of a micropolar fluid flowing past a curved surface has been studied [34C]. A discussion deals with the calculation of laminar and turbulent boundary layers on longitudinally curved surfaces [11C]. In [3C], the transonic laminar boundary layer flow near convex corners has been analyzed.

Flow and heat transfer over cylinders and spheres is the subject of a number of papers. Heat transfer from a slender cylinder in axial air flow has been measured [5C]. An investigation deals with skin friction and heat transfer on a cylinder moving through a stationary fluid [2C]. A numerical method has been used to determine the heat transfer from a circular cylinder impulsively started from rest [10C]. An experimental study deals with the effect of surface turbulizers on the local heat-transfer rate on a cylinder [14C]. The finite-element method has been applied to the flow around a circular cylinder [47C]. A two-equation turbulence model is used to investigate the effect of free-stream turbulence on skin friction and heat transfer around a circular cylinder in cross flow [44C]; good agreement with experiment is achieved.

A correlation is presented for the heat transfer from subcooled water films on horizontal tubes [39C]. A numerical method is used to analyze the variable property heat transfer to a single sphere in high temperature surroundings [37C]. Another study deals with the laminar boundary layer on an impulsively started rotating sphere [15C]. Heat transfer through the interface of spherical particles has been investigated for an unsteady situation [7C].

Impinging jets and stagnation-point heat transfer have been extensively studied. Experimental data and a simple correlation are presented for the heat transfer from an inclined rectangular plate of finite width [42C]. Measurements are also reported for the local and average heat-transfer coefficients for a square plate placed at various orientations to the flow direction [46C]. The stagnation-point heat transfer is studied with the inflow of a turbulized jet at a barrier [19C]. A discussion deals with the response of a stagnation boundary layer to a change in the external velocity [12C]. The mass transfer near the front stagnation point has been investigated in a fluctuating flow [4C]. A study describes heat and mass transfer from an axisymmetric jet impinging on a baffle [33C]. In a related work, the heat transfer in the vicinity of the stagnation point is measured for the situation in which a turbulized jet impinges onto a baffle [18C]. Local mass-transfer coefficients resulting from the impingement of a two-dimensional laminar jet have been measured with a holographic technique, and a correlation of the data has been obtained [29C]. A study has been made of the two-dimensional stagnation-point flow impinging obliquely on a plane wall [45C]. Another work deals with the heat exchange between a blunt body and a high-temperature gas jet [38C].

In a detailed experimental study of turbulent annular jets, the mean and fluctuating properties of the inner region have been measured [26C]. Measurements of temperature and velocity profiles are presented for heated three-dimensional turbulent jets from rectangular nozzles [40C]. Analysis is made of the stability and mixing of a vertical buoyant jet in a channel of confined depth [23C]. Measurements are reported for the heat-transfer characteristics of the impinging flow from a two-dimensional array of jets [31C].

FLOW WITH SEPARATED REGIONS

In a number of applications, the heat transfer in regions where the flow separates from a surface can be quite important. Several studies have been conducted which examine the heat transfer in a cavity placed in a wall over which there is a boundary layer flow. Others consider separation and reattachment and the resulting heat transfer following an abrupt change in the contour of a wall over which a fluid is flowing. Still other works consider the wake region behind a cylinder or other blunt body.

Different flow regimes have been visualized in a rectangular cavity of variable depth; heat-transfer measurements show significant variation of heat transfer with depth [12D]. An electro-chemical technique has been used to determine the mass transfer in a semicircular cavity in a wall [1D].

The heat transfer to a cylinder on which tripping wires are placed is closely related to the width of the wake region behind the cylinder [2D]. The statistical properties of the wake behind a heated cylinder have been examined [5D]. Experiments on heat transfer from a smooth cylinder [14D] and a rough cylinder [13D] demonstrate significant changes in heat transfer near the critical Reynolds number. Local measurements around a cylinder in crossflow show the influence of a spray of liquid on the cylinder [4D].

The nose shape on the front of a flat plate of finite thickness has a significant effect on the heat transfer in the separated and reattaching regions [7D]. The heat transfer downstream of a disc mounted co-axially on a smaller diameter cylinder arranged with axes parallel to the mainstream flow is a maximum at the reattachment point downstream of the disc [9D]. The heat transfer has been measured downstream of a rearward-facing step when the flow is generated by pulsating jets [3D]. Use of the electrochemical technique indicates that the maximum heat transfer downstream of a sudden expansion is well within the recirculation zone [10D].

Experiments related to wake regions include a measurement of the temperature characteristics in the turbulent wake behind an asymmetrically-heated plate [6D]. The effect of roughness on the separated region behind a flat plate has been studied [11D]. An analysis of the wake region behind a blunted cone in a hypersonic flow has been presented [8D].

TRANSFER MECHANISMS

Papers on transfer mechanisms deal with turbulence models, detailed measurements of turbulence, and theoretical analyses of turbulence growth and decay.

An algebraic model has been developed for stresses and heat fluxes in a turbulent shear flow with streamline curvature [12E]. A discussion deals with the prediction of turbulent Prandtl and Schmidt numbers from modeled transport equations [14E]. Reacting Couette flow is calculated by using an approximate theory developed to describe the combined effects of heat and mass transfer (30E). A version of a one-equation turbulence model has been presented for the calculation of free shear flows [11E]. A statistical model of turbulence is developed for two-dimensional mixing layers on the assumption that the turbulence is in a state of quasi-equilibrium [29E]. The use of subgrid-scale models for predicting turbulent flow is described in [6E]; the outcome of these models is compared to those used for large-eddy simulation, and it is suggested that the method could be used to predict the constants for the conventional models. Numerical modeling concepts are given for the turbulent mixing of large flows [21E]. Entropy generation due to finite temperature gradients and due to viscous effects is analyzed for pipe flow, flat-plate boundary layer, cylinder in cross flow, and entrance region of a duct [2E]. Development of a second-moment approximation to turbulent convection is discussed in [18E]; the turbulent heat fluxes are used as dependent variables of transport equations, and thus no assumption needs to be made for the turbulent Prandtl number. A discussion deals with the invariance of turbulence closure models [27E].

A number of papers report extensive turbulence measurements. Experimental data for turbulence are presented for a boundary layer on a rough wall with blowing and heat transfer [23E]. Experiments and analysis given in [28E] deal with the local isotropy and large structures in a heated turbulent jet. Hot-wire anemometry is used to measure the distortion of grid-generated turbulence by a circular cylinder [5E]. Measurements of turbulence in a mixed layer and through a density interface are made in the absence of a mean flow [20E]. Experiments are conducted to measure the fluctuations of turbulent shear in the shear layer of a circular jet [7E]. Detailed turbulence measurements have been made by introducing strong external disturbances into a mixing layer to observe the formation of coherent eddies [32E]. Experimental data are presented for various terms in the turbulent heat-transfer equation for a retarded boundary layer [26E]. Turbulent diffusion coefficients have been measured in mixing vessels [22E]. Experimental measurements have been performed for turbulence produced by a shearing instability in a two-fluid system [17E].

A theoretical study is made of thermal diffusion in an inclined column [1E]. Thermoconvective waves have been studied in a compressible fluid [16E] and in a conducting and radiating fluid [15E]. Theoretical discussions and analyses of turbulence fields have appeared in many publications [8–10E, 13E, 19E]. A statistical approach to turbulence has been developed in [31E], while the boundary layer transition is dealt with in [3E]. Properties of large structure in a turbulent duct flow are discussed [24E].

Also reported are the experimental data for turbulence in the continuous phase of fluid–particle systems [4E]. Another investigation deals with heat transfer in a ferromagnetic suspension under the action of a magnetic field [25E]; heat transfer is found to be enhanced in the direction of the field and decreased in the perpendicular direction.

NATURAL CONVECTION

Interest remains high in heat transfer by natural convection. As usual, there is a large number of papers related to convection in enclosures, particularly those heated from below. There is a good deal of activity in the numerical calculation of convection in vertical enclosures heated from one side and cooled on the opposing side. There also appears to be growing interest in natural convection in porous media.

A conference report on convection in fluid layers with buoyancy-driven flows has been published [56F]. An analytical and experimental study describes the instability of convection rolls in a layer heated from below [14F]. Hexagonal and roll cells are predicted for post-critical buoyancy and surface-driven flows [72F]. Introduction of a small amount of a third component can alter the stability criterion in doubly-diffusive convection [49F]. With a large variation in the viscosity of a fluid, stable rolls occur similar to those in a constant viscosity fluid [111F]. A numerical calculation indicates that the mode of circulation in a layer heated from below depends on the thermal boundary conditions and the aspect ratio [15F]. Measurements of the velocity distribution at low Rayleigh number, using scattered laser radiation, show the development of rolls [124F]. The instability in a layer of nematic liquid crystals has been observed [51F].

In a layer of fluid heated from below, the Nusselt number was found to increase somewhat at low aspect ratio [89F]. In a cylinder, the onset of flow at low Rayleigh number has been found to be very different from that in a large aspect-ratio horizontal layer [97F]; in the same system; use of a binary gas mixture yields a lower critical Rayleigh number [98F].

Reconsideration of turbulent convection data for a fluid layer heated from below suggests that more concern should be directed toward aspect ratio effects even at large Rayleigh number [29F]. A model to generalize results for both heating from below and horizontal layers with internal energy sources has been described [11F].

The unsteady temperature distribution has been measured in an evaporating water layer to analyze mixing at a water–vapor interface [6F]. Heat and mass transfer across an interface has been studied with application to film boiling [57F]. Heating a stably-stratified layer from below can result in a series of convecting layers [59F]. The heat transfer to a stably-stratified salt solution subjected to a steady lateral temperature gradient has been measured [140F].

Experiments on convection with internal energy sources and with different top and bottom layer temperatures yielded a correlation for the heat transfer [13F]. The onset of convection with non-uniform energy sources, as would occur in a fluid absorbing ionizing radiation, was predicted [145F].

Unsteady convection in horizontal channels with arbitrary temperatures has been calculated through to steady state flow [91F]. The reasponse to fluctuating thermal boundary conditions in horizontal layers has been measured [37F].

The cumulative effects of surface tension at an upper liquid–gas interface and heating of a horizontal layer from below have been examined [76F]. The surface tension-driven flow pattern has been calculated for a differentially-heated vertical layer open at the top [30F]. The influence of combined surface and buoyancy-driven forces on the stability of a liquid film flowing down a heated inclined wall has been analyzed [131F].

A number of studies consider convection in an inclined layer. Spatial perturbations are found to trigger instability in such a layer heated from below [45F]. The effect of boundary conditions on the stability of an inclined layer has been calculated [100F], as has the flow in such a layer with a square cross-section [101F]. Consideration of radiation and convective boundary conditions leads to critical parameters for the onset of the flow [54F]. Use of the Galerkin method to predict the Nusselt number at small angles of inclination yields results which are in good agreement with experimental data [35F]. Correlations have been obtained for convection in an inclined array of cells [36F]. Little effect of aspect ratio on heat transfer is found at different inclinations down to moderate aspect ratio [110F].

Natural convection in vertical layers with two opposing walls maintained at different temperatures and the upper and lower bounding planes adiabatic has been examined using a number of numerical schemes. Emphasis is on two-dimensional flow where no variation is assumed in the horizontal dimension parallel to the heated and cooled walls. A comparison of different numerical solutions for a square cavity has been presented [31F]. The maximum Nusselt number is found to occur at an aspect ratio near unity with the layer being slightly higher than it is wide [114F]. Specific calculations for the flow in square enclosures have been done using a finite element method [85F] and a high-order finite difference calculation [112F]. Other computational studies examine convection in a high aspect ratio slot simulating the vertical layer between window panes [52F] and compare flows in slots over a range of aspect ratios [64F].

A semi-empirical analysis provides Nusselt numbers for heat transfer across vertical enclosures [7F]. Experiments with a vertical layer indicate that an additional stable, vertical gradient retards the flow in a differentially-heated channel [99F]. The effect of finite conduction in the side walls of a vertical channel on the heat transfer has been analyzed [41F]. Additional numerical analyses include the development of algorithms for three-dimensional natural convection flows [103F] and a solution of three-dimensional transients in rectangular enclosures [16F].

The critical Grashof number for the onset of transverse rolls in a vertical layer is found to be almost independent of Prandtl number [113F]. Velocity and temperature fields have been measured for turbulent flow in a differentially-heated vertical layer [75F].

Several works consider the convection in a horizontal annulus formed by a solid circular cylinder inside a circular cylindrical cavity with the two surfaces at different temperatures. Multicellular flow has been found in such an annulus, particularly with a low Prandtl number fluid [18F]. A critical Rayleigh number has been found for the stability of a flow through an annular gap [92F]. Flow under transient conditions has been measured in an annulus [136F]. Convection with a non-uniform temperature on the outer cylinder in the form of a vertical gradient has been analyzed [125F]. The natural convection along an annulus when the temperatures at the two ends of the annulus are different has been studied to predict the horizontal flow in such geometry [10F]. The flow in both a cylindrical and spherical annulus with a porous media present has been examined.

The temperature distribution in a triangular enclosure has been measured using an interferometer [38F]. The effect of gas compressibility on thermal convection in a circular annulus has been predicted [71F]. Measurements of heat transfer have been made in partially-filled toroidal vessels [69F] and spherical cavities [70F].

A model of an open-loop thermosyphon has been used to simulate ground-water flow in aquifers [134F]. Flow in a toroidal thermosyphon has been studied experimentally and numerically with different regions heated and cooled [25F]. The effect of dissipation in a free natural convection loop has been analyzed [148F]. Transient behavior in a natural circulation loop has been studied with heated bottom and cooled top regions [48F] and with point heat sources and sinks [149F].

Work on natural convection boundary layers includes studies of the flow along a vertical heated plate. The use of a film temperature satisfactorily takes into account the effects of variable properties on heat transfer in a laminar boundary layer of water [119F]. The Grashof number by itself is found to be insufficient to define transition to turbulence in a boundary layer on a vertical surface [83F]. In a related study, different criteria for determining transition of a natural convection boundary layer on a vertical plate are compared [107].

Models for the outer and inner portions of a turbulent boundary layer are used to predict the Nusselt number along a vertical plate [44F]. Hot-wire measurements have been made in the transition region along a flat plate with a constant heat flux boundary condition [12F]. Analysis of the heat transfer from a vertical plate to a fluid near its thermodynamic critical point includes the effect of variable properties [117F]. Analyses for the transient boundary layer on a vertical plate include the effect of step changes in heat input [115F] and of surface temperature oscillation [94F].

Local non-similarity solutions show that the velocity field on an inclined surface is greatly affected by inclination while the temperature field and heat transfer are not very different from those with a vertical plate [53F]. Temperature and velocity distributions have been measured in the longitudinal vortex flow along an inclined heated surface [120F].

Studies related to the natural convection heat transfer from a heated horizontal circular cylinder include the development of simplified equations to predict the average Nusselt number over a range of conditions [40F]. Higher heat transfer from a cylinder can occur when it is immersed in a shallow pool of liquid as contrasted to a deeper pool [60F]. Different heat-transfer relations are required for cooling as compared to heating a horizontal cylinder in supercritical CO_2 [104F]. A boundary-layer analysis predicts the flow around a suddenly-heated cylinder [61F]; a numerical study of a similarly heated cylinder has been carried out to steady-state conditions [67F].

A boundary-layer analysis of the convection above a circular horizontal disc indicates the total heat transfer is chiefly due to the high rate of heat transfer at or near the outer edge of the disc [146F]. Heat transfer from a conical surface has been analyzed when the cone has a horizontal axis [142F] and when the cone has a vertical axis [2F]. A numerical study indicates the transverse curvature of a vertical frustrum of a cone significantly increases the rate of heat transfer [95F]. Approximate solutions have been obtained for the heat transfer from heated spheres and cylinders immersed in a thermally-stratified fluid [19F].

There is some interest in the natural convection in a fluid (usually water) in which the range of temperatures encountered includes the temperature at which the density is maximum. An analysis of buoyancy-induced flows in water includes the effects of both thermal and saline gradients [43F]; a related study considers flows adjacent to horizontal surfaces [42F]. Other studies in pure water which include the density maximum relate to heat transfer in a horizontal layer heated from below [86F] and convection in a porous medium [141F].

The influence of surface mass transfer on the heat transfer from a vertical cylinder increases with the Prandtl number of the fluid [90F]. Combined heat and mass transfer has been analyzed on an inclined surface [23F] and, in another study, on vertical, horizontal, and inclined surfaces [126F]. The effect of suction and injection on heat transfer from a heated cylinder has been examined [74F]. A good correspondence of the heat- and mass-transfer analogy is found when using the sublimation of naphthelene to study heat transfer even in the presence of humid air [129F].

A turbulence model is used to predict the flow and temperature distribution in the transition of a heated vertical jet into a buoyant plume [20F]; a related study examines the flow near the origin of the buoyant jet [21F]. An interferometric measurement agrees with similarity predictions of the flow in a plume above a point source, if one assumes an apparent source position [122F]. Streak photographs show the velocity field of a rising plume from a heat source [123F]. Related experiments on a rising plume fit a model for the initiation of the plume and motion of the plume cap [121F]. A similarity analysis of a transient plume predicts that the velocity of the leading edge is less than the velocity of fluid following it [28F]. Swaying motion is observed before transition in the plume above a horizontal line source [144F].

A local heat source on a horizontal surface below a stably-stratified fluid can lead to either plume flow or layers of flow cells, depending upon the specific boundary and initial conditions [133F]. Motion of a suddenly-released thermal in the form of a vortex ring has been studied analytically [17F]. The motion at a liquid–liquid interface upon which a submerged buoyant jet impinges has been examined [81F]. An analysis predicts the flow in the turbulent plume above a line source in a horizontal wall [84F]. The turbulence properties have been measured in a thermal plume rising adjacent to an isothermal wall [80F].

A number of studies have examined convection in horizontal layers of saturated porous media. Conducting side boundaries have a significant influence on the onset of convection in such a layer [82F]. The presence of either two- or three-dimensional flow at low Rayleigh number in such porous media depends on the initial conditions [132F]. The effects of isotropy on supercritical motion and heat transfer has been examined [78F]. Experiments have been performed with distributed energy sources within a porous horizontal layer [73F]. The transient behavior of a geothermal reservoir has been examined by considering the heat transfer through three horizontal layers of different porosity [109F]. The stability of a Hele–Shaw cell heated from below can be compared to non-linear convection in a porous medium [79F].

Flow regimes are predicted within an inclined porous layer, heated either from above or below [139F]. The Nusselt number has been calculated for a differentially-heated vertical slot containing a porous medium [8F].

High Rayleigh number boundary-layer predictions for convection in a saturated porous media are also useful at moderate Rayleigh numbers [24F]. The effect of surface mass flux on heat transfer from a vertical wall adjacent to a saturated porous medium has been analyzed [87F]. An analysis predicts the onset of longitudinal vortices in a porous media adjacent to a flat inclined surface [58F]. A relationship has been derived for the heat flow from two-dimensional and axisymmetric bodies of arbitrary shape immersed in a saturated porous medium [88F]. Under some conditions, jet-type flow can occur in a heated vertical wedge of saturated porous medium [46F]. Numerical solutions predict the natural convection in porous media around plates, spheres, and cylinders [4F]. A boundary-layer model predicts the flow of a vapor adjacent to a wall immersed in a liquid-saturated porous medium [102F].

A shadowgraph technique has been used to measure local heat-transfer coefficients on a cylinder immersed in a melting solid [5F]. Experiments have been performed on melting around a horizontal array of heating cylinders [108F]. The effect of natural convection on freezing about a vertical cooled cylinder has been studied experimentally [130F].

Several studies examine natural convection in rotating systems. Analysis on the natural convection in the annulus between two rotating spheres shows the possibility of strong secondary flows [32F, 34F]. The effect of rotation on thermal convection in water near its point of maximum density has been studied numerically [106F]. The heat transfer from an isolated rotating plate has been examined with a finite difference technique [138F]. Rotation is generally found to have a stabilizing effect on the potential motion of a two-component fluid layer heated from below [3F]. The temperature field has been measured in a heated spherical cavity which is partially filled with liquids and rotated [50F].

Electric and magnetic fields can play a role in buoyancy-driven convection. The influence of an alternating electric field on natural convection in an organic fluid is strongly dependent on the dielectric constant of the fluid [147F]. A magnetic field appears to decrease the Nusselt number for convection in a rectangular container [118F]. A transverse magnetic field has only a modest effect on the flow field above a line source on a vertical adiabatic wall [47F]. The influence of a magnetic field on convection in a layer heated from below has been analyzed [105F]. Combined natural convection with rotation in magnetic fields has been studied in an electrically-conducting fluid [128F] and in a ferromagnetic fluid [26F].

When heat transfer takes place with flow which is generated partly by some mechanism external to the region of interest, such as a pump or fan, and partly by buoyancy forces, the term mixed convection—or alternately, combined free and forced convection—is used. Such flows are common in many heat-transfer situations. Generally, any forced convection flow in a gravitational field will have some buoyancy forces due to temperature differences required to transfer heat. However, in cases where these buoyancy forces and their effects on the flow are small compared to the external forces, they can often be neglected. In other forced convection situations, the flow due to buoyancy is of the same order of magnitude as the forced flow and therefore cannot be neglected. When the buoyancy forces tend to generate flow in more-or-less the same direction as the forced flow, we say the flows are aiding; conversely, when the buoyancy-driven induced flows tend to be in the opposite direction from the forced flow, we say we have opposing flow.

Mixed convection with opposing flow on a vertical isothermal plate has been examined [135F]. The influence of dissipation on aiding flow along a semi-infinite vertical plate has been analyzed numerically [127F]. A similarity solution has been obtained for mixed flow over a horizontal plate with a non-uniform wall temperature [116F]. The critical Reynolds number for instability of mixed convection over a horizontal plate has been obtained [22F]. On an inclined flat surface, buoyancy increases the Nusselt number in aiding flow and decreases it in opposing flow [93F]. Unsteady mixed convection has been studied to simulate phenomena on a hot-wire anemometer exposed to a low speed flow [62F]. A numerical solution for unsteady flow on an isothermal circular cylinder has been obtained for aiding flow [68F].

A number of mixed flow studies have been concerned with heat transfer in enclosed regions, such as ducts. In the thermal entrance region of a duct, the heat transfer can be augmented by a factor greater than four due to natural convection instabilities [66F]. Combined convection has been studied in vertical ducts of arbitrary cross-section [27F]. The effect of combined convection on sublimation from a wall of a rectangular duct has been examined [143F]. The influence of through-flow on heat transfer in a long, slender, horizontal cavity differentially-heated at the ends has been examined [9F]. Combined convection has been examined for heat transfer in a partially-filled vertical cylinder [65F] and in a rotating spherical annulus [33F].

Natural convection is often of importance in problems related to the heating and cooling of buildings. The influence of buoyancy on the temperature distribution and flow in an enclosure for which there is through-flow have been studied with application to a ventilated room [96F]. An open rectangular cavity with different temperatures at the side wall and the bottom wall has been examined to simulate the flow in a passively-heated solar-thermal energy-storage system within a building [1F].

Several important techniques have been used for flow visualization or quantitative determination of the flow field in natural convection flows, which are usually at low speed. The thymol blue technique has been used in a glycerol–water solution to study motion over a range of Prandtl number from 7–1000 [137F]. The difficulty of measuring velocity in a natural convection field with a hot-wire anemometer has been described [63F]. Laser–Doppler techniques are particularly suited for measurements in low-speed flows, and they have been used to determine the velocity field in natural convection along a vertical flat wall [39F] and around a vertical cylinder [55F]. The deflection of a laser beam through a liquid heated from below has been used to indicate transitions in the flow [77F].

CONVECTION FROM ROTATING SURFACES

Heat transfer from axisymmetric line sources at the surface of a rotating disk into a laminar constant property flow has been calculated [8G]. A similar process of jet cooling at the rim of a rotating disk depends primarily on the ratio of jet flow rate to disk pumping flow [7G]. Experiments [12G] determined local heat transfer from a disk rotating in an enclosure. A linear theory [14G] considers how the boundary layers on the surfaces of two coaxial disks rotating with a slightly different angular velocity are modified when blowing occurs on one disk and suction on the second disk. Results of flow and heat transfer studies in the inlet zone of a porous tube with injection into the swirling flow were published [11G]. An empirical equation describing the decay of circulation of swirling flow in a pipe has been obtained from experimental results [9G]. Rotation was found [5G] to increase heat transfer in the inlet section of turbine blade cooling channels by a factor of 1.2 to 1.4. Experiments were performed [10G] to study heat transfer from a cylinder placed in a coaxial rotating flow. A Reynolds analogy solution [13G] describes heat transfer for combined Taylor vortex and axial flow through the annular space between an inner rotating and an outer stationary cylinder.

An experimental and numerical study [1G] considers the spin-up of a thermally stratified rotating fluid in a cylinder, the average velocity of which increases linearly in time. The spin-up adjustment was found slower than previously reported. Velocity profiles obtained by an analytical model [2G] for concentric flow between coaxial rotating cylinders with a stationary lower boundary agree well with experiments. A numerical solution [6G] of the steady axisymmetric incompressible laminar boundary-layer equations for swirling flow with heat and mass transfer in conical nozzles and diffusers agrees with solutions by integral methods except near the exit. The compressible boundary layer equations describing swirling flow in a nozzle or diffuser were transformed using Lee's transformation and solved numerically [4G]. It was found that the variation of the product density times velocity and mass transfer have a strong effect on heat transfer. The analytical solution describing the temperature distribution in laminar boundary layers on rotating bodies with non-uniform surface temperature are presented in the form of universal functions [3G].

COMBINED HEAT AND MASS TRANSFER

The concepts of eddy viscosity and mixing length were used to predict numerically [4H] the effects of tangential slot injection on turbulent boundary layer flow. The turbulence model in the shear layer near the slot had to be improved to obtain agreement with experiments. Measurements of film cooling effectiveness with injection from a single hole or a row of holes with 8, 5.33 and 2.67 pitch to diameter ratio and an inclination of 30° indicated the effects of stream turbulence and velocity gradients [3H]. The boundary-layer thickness, Reynolds number, stream turbulence intensity (0.3–20.6%) and turbulence scale (0.06 to 0.33 of the jet diameter) can affect film cooling performance significantly [9–11H]. Experimental studies considered film cooling in supersonic axisymmetric nozzles [26H] and in hypersonic flow [18H] with injection through a tangential slot to an isothermal wall. Hydrogen was found to be the most efficient coolant for constant mass injection rate because the mixing layer stays discrete and laminar.

A new approach [20H] correlates boundary-layer mass-transfer rates with thermal diffusion and variable properties for laminar flow and a wide range of Lewis numbers. Equations are presented [6H] describing heat-transfer properties for mass flow through perforated plates. Solutions [25H] for laminar flow at larger Schmidt or Prandtl numbers and for turbulent flow describe heat and mass transfer between a flowing fluid and a solid wavy surface for large and small wave numbers; experiments clarified the wave induced variation of the turbulent transport. Heat transfer in turbulent boundary layers was studied on a porous plate with a permeable zone of varying length and with injection of a cooling gas [2H], as well as with a porous wall with alternating injection and suction zones at a Mach number of 2 [12H]. Correction factors describe [19H] the influence of the Stefan flow on the Lewis factor for one-dimensional heat and mass transfer. Mass transfer studies [16H] in boundary layers of a non-Newtonian power law fluid included the effect of mass injection. Numerical solutions of mass transfer with chemical surface reaction are reported [22H] for flat plates. A computer technique for the study [13H] of steady and unsteady, turbulent, chemically reacting flows in axisymmetric situations uses the Patankar–Spalding method. Analytic methods are compared [5H] with experimental results describing gas turbine combustor cooling augmented by backside convection enhanced with transverse-rib turbulence promoters.

Binary laminar boundary layer flow along a vaporizing liquid layer is studied analytically [17H] for a co- or counter current liquid film. Turbulent heat and mass transfer by convection, radiation, and evaporation was studied [21H] on a rough air–water interface; a simple theory is used and compared with experimental results. Nusselt's theory is confirmed by an experimental investigation [14H] of local mass transfer in a laminar and turbulent falling liquid film at $Re = 3.86$ to 2496. A laminar stagnation flow boundary layer model [24H] predicts experimental results for surface ablation by melting in the impingement region of a liquid jet. A physical–mathematical model was used [15H] to calculate the time evolution of spherical droplets in a vapor environment. Low Peclet number heat and mass transfer from a dielectric drop suspended in an electric field is influenced by circular motion within the drop [7H]; an analysis using perturbations gives results valid to $Pe = 60$. Heat transfer from a wedge to air flow was increased from 2 to 14 times [1H] when water mist was mixed with the cooling air. Particle trajectories near an airfoil with a film cooled leading edge were studied [23H] analytically and experimentally by flow visualization in a cascade. They depend on two parameters. Most important of them is the Stokes number

$$St = \frac{\rho_p U_1 D_p^2}{18 \mu_1 b_x},$$

in which the subscript p refers to particles and the subscript 1 to cascade inlet conditions; b_x denotes the chord length. It is found that for $St < 0.1$ the particles follow essentially the fluid path, whereas for $St > 10$, most particles will impact. The deflection of the particles by leading edge film cooling is also shown. An analysis [8H] of heat and moisture transfer in concrete slabs considers the effect of material characteristics and the hardening of concrete.

CHANGE OF PHASE

Boiling

Similarity numbers were introduced to describe heat transfer in pool boiling [43J].

The heterogeneous nucleation theory can describe not only the onset of nucleate boiling but also the boiling crisis [22J]. The mechanical energy stability criterion is extended [47J] to describe pool boiling burnout. Previously published correlations for the critical heat flux in forced convection boiling in vertical tubes are compared with new experiments [34J] and are found useful. An extension of the previous analysis to annuli results in generalized correlations [32J]. Previously published equations for the critical heat flux density in free convection in boilers have been verified [84J]. Burnout in four-rod bundles with flow of water and Freon 12 was studied experimentally [60J]. Flow turbulization increases the critical heat flux density and the pressure drop in annuli [56J]. The critical heat flux is increased by a factor 1.2 to 1.5 with turbulence promoters in the form of transverse fins [55J]. The pressure drop also increases by a factor of 1.2 to 1.4. A comparison of experimental and analytical results for critical heat loads connected with boiling helium in tubes indicates that this process is still poorly understood [4J]. The hydraulic resistance and burnout with helium boiling in tubes was studied [15J]. Thermal fluctuations in the tube wall caused by transition boiling in sodium-heated steam-generator tubes were measured [19J]. An empirical formula was derived describing the limiting vapor quantity in the second boiling crisis [53J]. Analysis [25J] of nucleation processes in large scale vapor explosions is based on the assumption that spontaneous nucleation cannot occur until the thermal boundary layer is sufficiently thick to support a critical size cavity. An analysis of dryout and rewetting was published [73J] for a model reactor core.

A previous correlation for the critical heat flux of forced convection boiling in vertical tubes with inlet subcooling was used for an analysis of the process [33J]. The upper limit for the critical heat flux in saturated forced convection boiling on a heated disk with a small impingement jet was studied [35J]. A graphical method [68J] to predict the critical heat flux in vertical tubes agrees with a large number of published data. A post dryout analysis [31J] for upward flow in a vertical tube considers heat transfer from the wall to the vapor, from the vapor to droplets, and from the wall to dropets (a small contribution). The Leidenfrost phenomenon was studied [7J] for water, *n*-octane and carbon tetrachloride drops. Interfacial phenomena were observed [88J] in the interline region of a rewetting hot spot of a falling thin film. Large interline temperature gradients and superheats were found possible with a stationary or moving interline.

An analysis of boundary layer flow in forced convection film boiling [87J] demonstrates that the pressure gradient in the liquid dominates the dynamics of the flow of the vapor boundary layer. Transition and film boiling may coexist [26J] in boiling of nitrogen on a vertical fin. Useful considerations are discussed [46J] for film boiling of helium below the λ point.

The quasisteady assumption was useful in the analysis [91J] of transient film boiling on a sphere with forced convection. Transient heat transfer with boiling was also studied [82J, 83J] for a stepwise increase in heating. Transient heat transfer from liquid-surrounded electrically heated wires in natural convection was found [81J] quite different from steady heat transfer.

A blowing parameter was used to correlate experimental results [29J] for evaporation and breakdown of thin water films driven by shear stresses. Boundaries of the region of existence of nucleate boiling should be useful for the design of thin film evaporators [80J]. A critical thickness for breakup of films of boiling water was found [79J] to be a function only of the heat flux density. Fluid evaporation and boiling heat transfer were studied [86J] in the grooves of thin film evaporators.

Experimental results for the pressure drop in horizontal finned tube evaporators for boiling refrigerants were compared [10J] with calculations. Evaporative heat transfer was enhanced by 30–760% by internal fins in tubes when refrigerant 22 was boiled [41J]. The pressure drop increased by 10–290%. The effect of internal fins on heat transfer and pressure drop was also studied [16J] for Freon 22. The effect of surface roughness was found significant [37J] for boiling heat transfer to light hydrocarbons and nitrogen. Experiments [42J] established contributions under which heat transfer is improved in boiling liquid nitrogen or helium in capillary-porous bodies. Experimental data have been correlated [3J] for heat transfer with boiling of dissociating nitrogen tetroxide in vertical tubes.

The two dimensional and axisymmetric growth and breakoff of bubbles with small contact angle was analyzed [71J]. A model for the effect of droplet interactions on vaporization [77J] considers evaporation of a droplet inside a bubble. An interferometer was used to study a stationary evaporating ethanol meniscus [63J]. An analysis [64J] results in very high local heat fluxes near the interline. An analysis [38J] of vaporization of a disperse system of atomized liquid droplets flowing in line with an air stream indicates that serious errors may result when the system is simplified to one with an averaged droplet size. The effect of contact angle on bubble nucleation was studied [17J]. Integral forms of the heat transport equation are used [94J] to obtain numerical solutions for the growth and departure of a vapor bubble at a horizontal superheated wall. An analysis [51J] of single evaporating droplets in an immiscible liquid is compared with published experimental data. The classical theory of homogeneous vapor nucleation is extended [61J] to multi-component liquids. Random explosive destabilization of vapor film boiling on a surface at 850°C was studied in subcooled water [18J]. Experiments formed the basis of a mathematical model [8J] of dropwise evaporation with very high heat fluxes.

Condensation

Research devoted to the investigation of heat transfer during condensation included studies of film condensation, dropwise condensation, and condensation in two phase and multi-component flows.

Many authors addressed the problem of film condensation inside pipes and different geometries. A dimensionless correlation for predicting heat-transfer coefficients during film condensation in pipes was presented which was applicable for different fluids and over ranges of reduced pressure, saturation temperature, vapor velocity, vapor quality, mass flux, heat flux, Reynolds number, and Prandtl number [69J]. An experimental study of heat transfer with condensation of a moving vapor (Freon-21) on a bundle of plain horizontal tubes within a wide range of vapor velocities and heat fluxes demonstrated the influences of the condensate and vapor velocities must be taken into account [45J]. The approximate integral method was used to study laminar film condensation of pure vapors in tubes. The results demonstrated that the assumed velocity profile at the beginning of condensation is not very significant for the calculated condensation performance in the tube; however, increasing the external heat transfer and putting the tube in a vertical position improved the performance of the tube [49J]. An accumulation and analysis of experimental data recommended a correlation for the problem of condensation of flowing vapor on horizontal tubes in downward vapor flow [6J]. The results of an experimental study of condensation heat transfer in tubes suggested a new correlation for calculating heat transfer in complete condensation of steam in vertical tubes [9J]. A study of the influence of film condensation on the flow of the entrance region of a tube showed that the inlet region becomes shorter with increasing condensation rate. This was attributed to a dramatic reduction of the vapor speed which tends to support the growth of the vapor boundary layer in spite of the opposing effect of suction [48J]. An experimental investigation of steam condensation in an inclined bundle of tubes demonstrated the inclination of a multirow bundle intensifies heat transfer on the condensing steam side by eliminating the flooding of tubes by condensate running off from top to bottom tubes [70J]. An experimental investigation of steam condensation inside profiled horizontal tubes demonstrated improved heat transfer in a horizontal tube film evaporator [65J]. A similarity solution was formulated and numerically evaluated for the problem of film condensation on a vertical plate or cylinder. The calculated fin heat transfer was found to be markedly less than that which would have been predicted by an isothermal fin model [59J]. Based on experimental evidence, a curve was suggested for film condensation of vapor in the absence of an appreciable external friction on the gas–liquid interface. The curve is quantitatively very similar for different geometries and reveals the regions of laminar wave motion, quasi-selfsimilar heat transfer, and fully developed turbulent heat transfer [44J].

The influence of material properties on dropwise condensation was also an area of strong interest. An experimental study performed to determine the least thickness required for an electroplated gold surface to promote dropwise condensation of steam at atmospheric pressure demonstrated that gold deposits of 500 layers or more resulted in dropwise condensation. Deposits of a hundred layers or less resulted in filmwise condensation and a transition region occurred between these two limits [93J]. For droplets condensing on or evaporating from a solid surface, the effects of the solid material properties and the droplet contact angle were analyzed by solving the steady heat conduction equation for the geometry of a spherical segment droplet on a semi-infinite solid. By assuming heat is transferred to or from the solid, only through the droplet, and that there is perfect thermal contact at the solid–liquid interface, solutions were found for the overall heat flow through the droplet [66J]. An experimental investigation of dropwise condensation of different steam/air mixtures on copper, aluminum, and nickel substrates, showed that the heat flux, the heat-transfer coefficient, and the surface temperature were observed to be highest on copper and lowest on nickel substrates for the same identical test conditions. Experimental results also demonstrated that the presence of non-condensable gases is an inhibiting influence on the heat-transfer performance in the condensation of steam. From a mathematical model of the problem, it was concluded that the minute fraction of the substrate surface covered by liquid droplets was most effective for the flow of heat and that the contribution to the heat transfer by the bare area was negligible [1J, 2J]. The high rate of heat transfer of dropwise condensation, as well as its limits, were explained on the basis of the behaviors of sub-microscopic active drops. Numerical analysis and consideration of the non-dimensionalized forms of the basic equations resulted in an expression for the Nusselt number for dropwise condensation in terms of a few characteristic parameters [76J].

Investigators also studied the problem of heat and mass transfer during condensation of multi-component and two phase flows. The problem of binary vapor condensation in the presence of an inert gas was studied to analyze the effect of the nature of the inert gas and its composition on the condensation process. The results of the computation show that diffusional interaction effects are significant for small concentrations of inert gas [40J]. A numerical study of laminar flow transport of binary vapor–gas mixtures in channels with porous walls and of removal of the condensing component by suction through these walls showed that the transport processes depended significantly on variations in physical properties, variability of the composition of the flowing gas mixture along the channel, and on transverse flow [72J]. A simplified analysis was presented for calculating condensation fluxes from multi-component vapor mixtures, taking into account the diffusional interactions in the vapor phase [39J]. The hydrodynamics of condensation of the stream in a moving two phase film were studied and working equations were obtained for determining the average fraction voids, hydraulic drag, and the volumetric heat-transfer coefficient [36J]. A significant reduction in computing time and memory requirements was obtained for the numerical computation of non-equilibrium condensation in one and two dimensional supersonic two phase flows [50J]. A method presented for solving the two phase boundary-layer equations for the condensation of flowing vapor on a horizontal cylinder provided numerical solutions for the distribution of the local values of the Nusselt number on the periphery of the cylinder as a function of different governing parameters [20J].

A miscellany of papers defied simple categorization. The results from a theoretical and experimental investigation of the hydrodynamics and heat transfer with steam condensation on vibrating horizontal tubes demonstrated that tube vibrations can lead to a 12% decrease in heat exchanger performance [67J]. Data presented for the boundary conditions of constant heat flux and constant wall temperature for a rotating heat pipe condenser demonstrated that an efficient spray cooling mechanism can be used to increase heat-transfer coefficients. However, there appears to be an upper cooling water flow rate above which dry saturated conditions cease to exist over the entire condenser length [13J]. A theoretical solution was presented for the problem of steam jet condensation in a parallel flow of liquid. An accompanying experimental investigation of steam condensing in a cocurrent and in a countercurrent flow of turbulent flowing water demonstrated general agreement with theoretical predictions of the level of the intensity of heat transfer [30J].

Two-phase flow

An analytical study was performed to evaluate the surface heat flux and the boundary-layer structure over an isothermally heated circular cylinder subjected to evaporating particle–vapor flow in forced convection. The results showed that enhancement of heat transfer is comparatively small in cases where there is large temperature difference, but distinctly large in cases involving large particles [54J]. The effects of the flow rate and the concentration of solid particles in the slurry on the pressure drop were investigated in solid–liquid two-phase flow in a horizontal pipe with low flow rates [78J]. The deposition motion of liquid drops in dispersed flow with heat addition was analyzed and an expression was suggested for the reaction force on the drop due to non-uniform drop evaporation inside the laminar sublayer. The effects of the drop diameter, deposition velocity, slip velocity, and wall temperature on the drop trajectory were examined [21J]. A method was presented for predicting local Nusselt numbers for heat transfer to a stratified gas–liquid flow for turbulent liquid/turbulent gas conditions. Liquid Nusselt numbers predicted by an analogy between momentum transfer and heat transfer were in agreement with experimental results for wavy interfacial conditions, and the circumferential average gas phase Nusselt numbers were in rough agreement with the Dittus–Boelter equation for single-phase flow based on flow through a conduit of irregular shape [14J]. A technique was developed for ascertaining thermocapillary movement of gas bubbles in various organic melts contained in a heated horizontal tube. In a related paper, the vapor pressure of the liquid and the composition of the gases in the bubble were shown to have a profound effect on thermal transport in the bubble, and hence, on the temperature gradient on the surface of the bubble [58J, 90J]. A theoretical analysis based on the premise that fluid flow results from the London–van der Waals dispersion force was used to evaluate the changing profile of an evaporating meniscus as a function of heat flux. The useful capillary pressure of the meniscus was significantly reduced as the interline (junction of solid–liquid–vapor) heat flux was increased [89J]. Heat- and mass-transfer mechanisms were theoretically studied for several capillary groove configurations and the effects of the solid–liquid–vapor interline heat transfer were isolated and evaluated. A method was provided for predicting surface heat-transfer coefficients for surfaces wetted to capillary grooves and basic information about heat transfer in the vicinity of the meniscus attachment region [27J]. Experimental data were obtained using propane to quantitatively determine the deterioration of temperature separation when the condition at the inlet fluid to a Ranque–Hilsch tube becomes a saturated mixture. Observations indicated that temperature separation diminished rapidly for inlet qualities of less than 80%, largely due to the increase of the "hot side" temperature [12J]. Experimental measurements were used to propose an empirical formula for predicting the pressure drops due to pipe bends in single-phase and air–solids two-phase flows in circular and eliptical bends [52J]. Numerical calculations over a wide range of temperatures characterized the effects of heat transfer on the behavior of the bubble and the impulse pressure in a viscous compressible liquid [85J].

Melting and freezing

A significant number of papers were concerned with the problem of heat transfer during melting. An experimental study performed on a horizontal flow of equally spaced heating cylinders melting a mixture of sodium nitrate and sodium hydroxide presented results for the timewise distribution of the melting coefficient for both single and multiple cylinders [62J]. The shape of the melting fronts and local heat-transfer coefficients were determined for melting from an array of electrically heated cylinders embedded in a paraffin (*n*-octadecane). Results indicated that natural convection effects are an important influence on the melt shape, surface temperature, and heat transfer coefficients [5J]. Visual observations from an experimental study of the melting of a horizontal slab of frozen olive oil placed underneath a pool of warm water showed that the melt removal is governed by Taylor instability and that melt releasing nodes lie at about a Taylor wavelength apart. Predictions of the growth of the interface based on equilibrium between surface tension and buoyant forces compare well with experimental data [75J]. An experimental study was made of the velocity profiles which result from the free convective melting of a vertical ice sheet into fresh water at temperatures in the range of 2–7°C. Results suggest that: (i) below 4.7°C, upward flow exists; (ii) above 7°C, entirely downward flowing boundary layers are suggested, and (iii) for intermediate temperatures, an oscillatory dual flow regime is indicated [92J]. An experimental investigation of the melting of a paraffin (*n*-octadecane) from a heated vertical wall of a rectangular test cell provided evidence of the importance of natural convection on heat transfer in the melt region. These conclusions were based on the resulting melt shapes, the temperatures in the paraffin, and the heat-transfer coefficients at the solid–liquid interface, and in their timewise variation [23J]. The problem of turbulent flow past freezing or melting ice was formulated for the case of random boundary waves. The methodology presented provides a means for determining the phase shifts between the streamwise distribution of turbulent transfer between wavy boundaries and the flows past them [28J].

Experiments were performed for freezing under conditions where the liquid phase was either above or at the fusion temperature. Freezing occured on a vertical tube housed in a constant temperature cylindrical vessel and the phase change medium was *n*-

eicosane. In the presence of liquid superheating, the freezing process was dramatically slowed and ultimately terminated by natural convection in the liquid [74J]. A study of the freezing of a liquid in turbulent flow inside a circular tube whose wall is kept at a uniform temperature lower than the freezing temperature of the liquid was solved. The radius of the solid–liquid interface and the local wall heat flux were determined as a function of time and position along the tube for different values of the Prandtl number and the freezing parameter [11J]. The phenomena of salt rejection during the freezing process of saline solutions in cells were investigated both analytically and experimentally. When freezing proceeds, in the solid–liquid region, freezing fronts were found to occur stepwise within several adjacent cells, due to the depression of the freezing point caused by salt rejection in the cells [24J]. An experiment performed to investigate the behavior of bubbles at a solidification interface and in the melt ahead of the interface in a low gravity environment observed that a larger number of trapped bubbles were present in the low gravity specimens, indicative of easier bubble nucleation, and that the morphology of the grown-in voids was dependent upon the applied temperature gradient [57J].

RADIATION

Radiation in participating media

Exact radiative transfer solutions are obtained for an isothermal medium confined within an isothermal enclosure using band radiation and diffuse reflections [20K]. An asymptotically exact approximate method of analysis for band radiation makes direct use of band absorption formulations for absorbing–emitting media. The method has acceptable errors even for low order approximations [21K]. The advantage of the P_3 approximation for solving higher order differential equations of radiative transfer is discussed and this approximation is used for solving the radiative exchange for the case of a participating medium between plane parallel plates, concentric cylinders, and concentric spheres [4K]. Based on an iterative solution for anisotropic radiative transfer in a slab, results have been obtained for the hemispherical reflectivity and transmissivity of the slab over a wide range of parameters [25K]. A new diffusion model for radiative transfer in particulate media extrapolates the conventional Eddington approximation to problems involving large absorption [18K].

A new six-flux model for radiative transfer should prove to be a useful component for incorporation into existing procedures for complete mathematical modeling of rectangular furnaces and heaters [23K]. A collocation method using B-splines as approximation functions appears to be an attractive, non-iterative candidate for the solution of combined radiation–conduction problems pertaining, for example, to LMFBR core disruptive melt down accident analyses [7K].

The band absorption of radiating gases can be incorporated into the three-dimensional differential approximation without increasing its complexity [19K]. Considering the effect of molecular gas radiation upon the thermal development downstream from a step change in wall temperature, one finds that even in the entrance region, self absorption by wall layer gas blocks significantly the radiation exchange between the gas core and the wall [3K].

A study of the interaction of radiative and convective transfer for slug flow of an absorbing–emitting gas in a black wall circular tube with specified wall heat flux shows that the outlet surface temperature has a strong influence on the temperature distribution particularly those for the wall and is even felt by the wall zones near the duct inlet [8K]. Calculations of the emissive power and of the radiative fluxes at the boundaries of a two-dimensional, finite, planar, gray, absorbing–emitting–scattering medium bounded by non-isothermal black walls demonstrate that any step variation in the wall temperature can be expressed in terms of universal functions for the semi-infinite step variation in wall temperature [12K]. Considering an absorbing–scattering slab bounded by emitting and reflecting parallel surfaces, the authors of this paper show how the emissivity and reflectivity of the bounding surfaces and the scattering properties of the participating medium affect radiative transfer within this medium [5K]. Studies of the radiative properties of a finite scattering medium bounded by a diffuse substrate indicate that the scattering layer acts as a source if the substrate emittance is less than the emittance of a semi-infinite scattering medium. Conversely when the substrate emittance is greater, the scattering layer acts as a shield and decreases the apparent emittance [10K]. Experimental studies of two-dimensional scattering in a medium of finite thickness show fair agreement with theoretical predictions [16K].

For predicting radiative transfer in aqueous suspensions a three-flux model is proposed consisting of refraction at the air–water interface, the highly anisotropic scattering in the suspension, and the diffuse reflection at the bottom. Excellent agreement is obtained between predictions of the net radiative flux in the suspension and measurements obtained for a suspension of unicellular algae [14K]. Solutions of the radiative transfer equation in shallow ponds show that scattering is not important when the albedo is small ($\omega \leq 0.5$) and the phase angle function is highly forward peaked. Therefore, even the simple Beer's law expression provides accurate predictions [13K]. By using a tunable far IR optically pumped laser the reflection and transmission of water at 25°C have been determined from which the complex index of refraction can be derived [24K]. Predictions based on two-dimensional multiple scattering with absorption are in fair agreement with experiments using a medium consisting of water and various concentrations of white latex paint [17K].

A proposed method for calculating radiative heat transfer in rod bundles relies on combining similar surfaces for the radiative heat-transfer calculations and identifying droplets and vapor as groups of absorbing media. The results show that the cooling of the hot rods is strongly influenced by radiation absorption of droplets when the droplet size is small [27K]. An iterative method for solving the radiation transport equation is very effective in the case of a two-phase medium of cylindrical geometry [1K].

Measurements with a newly developed system (differential absorption lidar) for remotely determining profiles of H_2O vapor concentrations in the atmosphere compare favorably with results obtained with rawinsondes [6K]. Studies of the aerosol extinction in various weather situations show that the air humidity affects the aerosol extinction mainly through modification of the particle size distribution. The humidity influence on the refractive index is less important [22K]. Recent advances in electro-optical instrumentation and in computer technology resulted in the elucidation of the effects of ozone absorption, the identification of a cloud bow on Venus, and the interpretation of Rayleigh scattering on Jupiter [9K].

In connection with radiative transport in liquids and solids a new formulation of the directional emittance of a semi-infinite scattering medium is suggested and numerical results are presented for a wide range of albedos and refractive indices [11K]. Calculations of the temperature distribution in a semi-transparent slab (optical window) reveal the importance of radiation. Results obtained for opaque boundaries are in good agreement with exact formulations found in the literature [2K].

It is shown that radiative interaction in laminar compressible boundary layers for moderate Mach numbers leads to a considerable increase of the thickness of the thermal boundary layer and tends to flatten temperature profiles [26K]. Transport of radiative energy at cryogenic temperatures is treated by an approximate method. Calculations of the time required for thermal stabilization of a system of metal screens is in agreement with experimental findings [15K].

Surface radiation

Total hemispherical emissivity values have been reported [9L] for stainless steel AISI 304 with a polished and electroplated surface in a temperature range from 340 to 1100 K. The measured values are very close to those published by Davisson and Weeks. Closed form expressions are presented [2L] for spectral hemispherical radiative properties. Modelling of the atmospheric effects in space measurements of ground reflectances has been discussed [12L].

Shape factors have been calculated [5L] for radiative exchange between coaxial annular disks of different radius ratio separated by a solid cylinder using the contour integral method. The same method was used [6L] to obtain shape factors in semi-closed form for radiative exchange between an end plane and the outer wall of concentric tubular enclosures. The results of a computer program [7L] using the Monte Carlo method for the analysis of three-dimensional radiative exchange factors for non-gray, nondiffuse surfaces compare well with the results of some space shuttle experiments. An efficient technique [8L] considers heat conduction in a wall with radiation across a gap. Experiments on convective heat transfer between cylindrical objects located in a channel and the channel wall have to account for radiative exchange. This problem is treated in [1L]. An analysis [3L] considers radiative exchange between diffusely emitting and specularly reflecting axisymmetric surfaces of enclosures, passages, and cavities. It is used to calculate radiative exchange between parabolic reflectors and a heat source located at their focus. Experiments [4L] considered transient heat exchange between a radiating plate and a high temperature gas flow.

Melting of an ice layer adhering to a vertical surface produced a rough surface when heated by short wavelength radiation, but a smooth surface when heated with long wavelength radiation [11L]. The rate of melting was well predicted by an analysis using a band model extinction coefficient. Back melting on a substrate covered by a horizontal cloudy ice layer was observed [10L] when it was exposed to radiative heating. Perturbation solutions [13L] to one-dimensional phase change on a fixed boundary subject to convection and radiation agree well with earlier work. The radiative term was approximated by a Taylor series.

MHD

Increasing emphasis on MHD generators seems to revive research activities in this field.

Radiative heat transfer in a MHD generator increases the heat flux to the walls and alters the gas temperature distribution in the channel. Real gas results differ substantially from those for a gray gas [9M]. In closed-cycle MHD generators a small amount of an alkaline metal is added to the working fluid (inert gas). Fog formation greatly reduces the deposition of the metal from the gas onto cold surfaces of the condensing heat exchanger [1M]. Experimental studies of residual disturbances in turbulent MHD flows after laminarization show that an almost undisturbed laminarized flow is obtained by eliminating entry effects [4M].

Studies of MHD Couette flow including Hall and ion-slip effects show that the Nusselt number depends in a rather involved way on the Hartmann number, the Hall parameter, and the ion-slip parameter [10M]. The flow of a hot, ionized fluid in a rectangular MHD channel is considered with significant heat transfer by thermal radiation. The temperature profiles are considerably distorted from those of uniform wall temperature when the walls are differentially and nonuniformly heated [6M]. Calculations for incompressible MHD flow between inclined walls indicate that in the approximation of constant fluid properties, the onset of flow separation is independent of heat transfer [5M].

Considering the effect of massive blowing rates on the steady laminar hypersonic boundary layer flow of an electrically conducting fluid in the stagnation region of an axisymmetric body in the presence of a magnetic field, one finds that massive blowing rates remove the viscous layer from the boundary, whereas the effect of the magnetic field is just the opposite [7M]. There are substantial magnetic field effects on the response of a cylindrical Langmuir probe when the probe's sheath is comparable to or greater than the Larmor radius [11M].

Ferromagnetic fluids can be used for controlled cooling of current-carrying conductors [2M]. Convective heat transfer in ferromagnetic fluids can be controlled by the application of homogeneous magnetic fields [3M]. Heat transfer to a cylinder in cross flow of a magnetic fluid can be substantially increased by applying an inhomogeneous magnetic field [8M].

MEASUREMENT TECHNIQUES

The development of instrumentation and measurement techniques related to heat-transfer studies are described by a number of researchers. The continued development of hot-wire anemometry and laser–Doppler anemometry for a wide variety of convection heat-transfer studies has been reported. There has been an increase in the number of papers which describe specialized techniques and instrumentation for performing measurements in two-phase flow and plasma processes.

A data reduction technique has been presented which permits constant-temperature hot-film and hot-wire probes to be used to determine flow angles and velocities for a wide range of supersonic and hypersonic flow conditions [24P]. An improved technique is proposed for making velocity measurements in unsteady flow studies where accuracy is the dominant consideration rather than frequency response [9P]. The attenuation of turbulence and mean velocity signals due to the line averaging imposed by hot-wires when used in the wake of a cylinder can be minimized by the proper selection of wire length [44P]. The flow patterns in highly-turbulent regions between cylinders have been determined using a process whereby a single hot-wire probe is rotated to three discrete positions and the three equations thus obtained are solved iteratively [48P]. The dynamic calibrations of hot-film and modified hot-wire probes were studied in order to assess their suitability for use in the measurement of turbulent fluctuations in compressible boundary-layer flows [2P]. If short probe cables are used on a simple constant-temperature hot-wire anemometer, the frequency response is limited by the finite open-loop gain of the amplifier used in the anemometer system [33P]. The calibration of probes at Reynolds numbers less than two at various Knudsen numbers show that a previously proposed relationship between the Nusselt and Reynolds numbers is valid, even for short wires [47P]. Temperature-sensitive constant-current hot wires operating at very low resistance ratios exhibit a significant increase in their temperature fluctuation response at a frequency of approximately 1/6 Hz [38P]. The theory of the transient hot-wire cell for measuring the thermal conductivity of gaseous mixtures has been reworked to include the coupling between the transport of energy and mass that exists in a mixture [28P].

Results of a calculation of the axisymmetric thermal gradient and viscous shear layers over a heated spanwise strip on an insulated cylinder in a periodically-reversing flow have been applied to the calibration of a hot-film probe used for *in vivo* blood flow velocity measurements [50P]. The frequency response on conical and wedge-shaped hot-film probes is strongly dependent on the geometry of the backing material [11P]. The calibration of cylindrical hot-film velocity sensors with aspect ratios near 20 obey a somewhat different heat-transfer relation than do large aspect ratio hot wires [5P].

A number of papers discuss the theory and application of laser–Doppler anemometry (LDA). An experimental method is proposed for estimating and correcting the effect of interaction of laser beams with turbulent temperature fluctuations along the beam paths in order to apply LDA to turbulence measurement in non-isothermal flows [35P]. Correction equations have been derived for the sensing volume and the individual realization biasing, and the equations have been applied to two-component flow fields measured by a one-dimensional LDA system [45P]. An analysis of Gaussian beam effects indicated that both axial and lateral frequency gradients can exist in the probe volume of improperly-aligned LDA systems [17P]. A technique is reported that facilitates measurement of the flow field in the cylinder of an internal combustion engine [16P]. The temperature, concentration of species (neutral as well as ionized) and velocity in jets, flames, and shock tubes can be obtained by the combined use of Raman scattering and laser–Doppler velocimetry [31P, 32P].

Three other velocity measuring approaches were described. The theory of the measurement of velocity by electrodiffusive sensors with conical and wedge-shaped working surfaces have been analyzed, and theoretical equations for determining amplitude and frequency characteristics have been suggested [39P]. A compact three-tube offset-geometry pressure probe, which is a combination of a total head tube and a Conrad probe, can be successfully used to determine the velocity vector in a subsonic flow [40P]. The use of a white light fringe image velocimeter (WFIV) has been shown to deserve serious consideration as a practical technique for laminar flow measurements [13P].

Instruments and techniques for performing radiation measurements have been described. A continuous-temperature IR calibrator provides reference video signals for temperature measurements which are made using an infrared scanner [26P]. A broad-range radiometer (0.25–20 μm) has been developed which incorporates a split-disk, windowed-design bolometer to facilitate measurements in the solar spectral range and is easily convertible to IR usage by the removal of the window [41P]. Energy photometry and spectral measurements of radiation detectors have been discussed [42P]. Three new surface treatments have been described that are satisfactory diffusers of infrared radiation for use in an integrating sphere pyrradiometer [10P]. Two sensitive optical techniques are useful for the study of small reflectance or absorptance differences between two interfaces [27P]. The absorption coefficient of low-loss materials (e.g. KCl) can be measured by calorimetry using pulsed CO_2 lasers [36P].

Development continues in the area of transport property measurements. A comparative method of measuring thermal conductivity is described which does not require calibrated thermometers and which involves temperature rises of less than 1 K while maintaining an uncertainty of $\pm$ 5% [30P]. The use of an apparatus for measuring the thermal conductivity, thermal diffusivity, and specific heat of reactor materials at elevated temperatures has been demonstrated [6P]. A transient hot-strip method has been developed for simultaneously measuring the thermal conductivity and the thermal diffusivity of solids and fluids with low electrical conductivity [22P]. A new contactless method has been used to measure the thermal conductivity of thin layers of solids with results deviating less than 15% from tabulated values [14P]. The thermal conductivity of a number of liquids has been measured using a newly-proposed spherically symmetrical apparatus [49P]. A thermal relaxation method can be used to measure heat capacities of samples which are as small as 10 mg [23P]. The steady shear viscosity of a viscoelastic fluid at low shear rates can be determined using a falling ball viscometer if appropriate analytical and experimental procedures are adopted [15P].

A variety of measurement techniques have been applied in experimental investigations of plasma processes. The plasma diagnostic applications of a pulsed, watt-level, low-pressure far-IR laser have been discussed [21P]. An improved circuit for the measurement of the electron energy distribution in a plasma makes it possible to simultaneously eliminate the fluctuation of plasma space potential, the deviation of dc probe voltage, and the attenuation of the second derivative signal during measurements [34P]. Using microwave techniques, a fast-scanning heterodyne receiver has been developed that scans 60–90 GHz every 10 ms, and the receiver was interfaced to a computer for completely automated calibrated temperature measurements of a high-temperature plasma [19P]. A four-framing Mach–Zehnder interferometer was used to observe the behavior of a plasma in a plasma-focus discharge [25P]. A modified foil-transmission technique facilitates the measurement of the temperature and the fractions of thermal and superthermal electrons in laser-produced plasmas [20P]. A feedback stabilization technique has been described for a fractional fringe interferometer for measuring plasma electron densities [43P].

There was an increase in the number of papers that described procedures and instruments for the study of two-phase flows. A radio frequency probe can be used to measure local void fractions and interface velocities in a gas–liquid two-phase flow [1P]. The principles of ultrasonic thermometry were used to detect and locate critical heat flux in a tube bundle with non-uniform axial heat generation [8P]. A technique based on scattering and transmission of fast neutron beams provides good sensitivity for the measurement of void fractions and phase distributions in transient flow boiling studies [7P]. A modified Gardon-type heat flux meter can be used effectively to provide reproducible measurements of the entire boiling curve during quenching experiments [46P]. The use of electrodiffusion measurement techniques was proven effective in the study of nucleate boiling heat transfer [12P]. Optical methods for the measurement of temperature in high-temperature flows of gas–solid suspensions were found to be sensitive to the concentration of solids but not sensitive to particle size [3P]. Direct measurements of bubble sizes in a fluidized bed can be obtained with an optical probe which uses light-emitting diodes as light sources and photocells as detectors [18P].

The use of universal extension leads for high-temperature thermocouples has been described [29P]. The influence of conduction between the sensor and its supports on the response of a resistance thermometer used to measure temperature fluctuations has been evaluated [37P]. An automated hybrid digital–analog system for processing the data of transient thermal experiments was examined [4P].

HEAT TRANSFER APPLICATIONS

Heat exchangers and heat pipes

Heat transfer and pressure drop was measured for inline and staggered tube bundles in cross flow [29Q] for Reynolds numbers between 5×10^4 and 2×10^6 and for Prandtl numbers between 3 and 7. Average heat transfer and pressure drop data for the same tube and flow arrangement were obtained [28Q] for high Prandtl numbers (between 100 and 14 000) and small Reynolds numbers (from 1 to 2×10^4). The velocity and temperature field as well as the turbulence were also measured [27Q] for $Pr = 2540$ and $Re = 500$. Equations for a single cylinder were adopted [4Q] to describe heat transfer in single rows and in bundles of tubes for transverse flow by addition of proper correction factors so that agreement with published data is obtained. An approximate calculation procedure [9Q] for axial coolant flow through rod bundles considers the space as interconnected cells. Convective heat transfer from an inline tube bundle to flow inclined towards the tube axis has been reported [13Q]. Equations describing the resistances of finned tube bundles were developed [11Q] using extensive available data. A generalized procedure [23Q] for the optimization of wavy condensing surfaces extends the work of Zener and Lavi.

Limitations on the heat exchanger performance imposed by the second law of thermodynamics are discussed [24Q] using the effectiveness-NTU method. A method to determine the relation of heat flux per transfer area or volume of a heat exchanger to the required power consumption to move the fluid is presented in [26Q]. An approximate equation [17Q] describes the mean temperature difference for eight air-cooled cross-flow heat exchanger arrangements using the effectiveness of the process stream and NTU of the air side. Heat transfer, pressure drop, and performance relations have been obtained for inline, staggered, and continuous plate heat exchangers [20Q] by numerical solutions of the flow and heat-transfer equations. The results are found to depend on one dimensionless parameter. Under most conditions, but not always, staggered arrays were found to have better performance. An improved procedure [5Q] is described which corrects the equations for mean transfer coefficients on the shell side of shell and tube heat exchangers with segmented baffles with transverse flow through the tube bank for leakage, bypass, and irregular flow pattern. A computer calculation [12Q] optimizes the fin side design of compact tube-fin heat exchangers with rippled fins for Reynolds numbers lower than 1200. Equations are developed [14Q] for the calculation of high performance finned tube heat exchangers for flue gases. Work on two-phase flow in shell and tube heat exchangers (condensers, boilers) at NEL, UK is reviewed [6Q] and correlations are obtained for the pressure drop.

The model of a thick-walled recuperator in continuous operation is used [25Q] as an analog for the transient performance of thermal regenerators. An analytic solution to the electric analog simulation of a regenerative heat exchanger with time varying fluid inlet temperature [16Q] considers discrete space steps but continuous time. Good agreement with Hausen's simplified method is obtained. A computer analysis

[18Q] of the regenerator with periodic heat storage is presented. A finite difference calculation [8Q] considers combined heat and mass transfer in regenerators with hygroscopic material. Sulphur attack was found to be detrimental to rotary ceramic heat exchangers [2Q].

An analysis [15Q] considers turbulent flow and pressure losses behind V-shaped oblique high resistance heat exchangers.

An analysis [22Q] of steady, laminar, incompressible flow in a flat plate heat pipe with adiabatic top plate agrees well with experiments on a porous plate model. Experiments [1Q] with gravity-assisted copper–water heat pipe showed that the heat-transfer capability is limited by the onset of film boiling in the evaporator zone. The heat-transfer characteristics of 35 wicks were investigated by experiments in the heating zone [21Q]. For low temperature heat pipes, no boiling occurred inside the wick at high heat flux densities. The Marangoni effect is proposed [3Q] to explain capacity degradation in axially grooved heat pipes when used with a control gas. Analytic predictions for a liquid-trap heat pipe using ammonia [7Q] agree well with experiments. Formation of noncondensible gas was observed in commercially available helium and stainless steel heat pipes filled with methanol or ammonia after 11 000 h [10Q]. Variable conductance heat pipe radiators for spacecraft maintained temperatures between 30 and 40°C at a temperature difference within 5°C [19Q].

Aircraft and space vehicles

An analysis of thermal louvers used for active temperature control in spacecrafts provides a description of the thermal features of non-isothermal louvered panels and yields convenient procedures for evaluating thermal gradients and heat-transfer rates [3R]. An analysis aimed towards optimization of movable louvers yields closed-form expressions for calculating effective emittance, solar rejection capability, and base surface temperature required for active thermal control. Comparisons with experimental results obtained for thermal control louvers used on the ATS-F & G spacecraft show good agreement [1R].

Studies of temperature sensitivity and erosive burning in solar rocket motors show that for typical composite propellants erosive burning increases both temperature sensitivity and pressure exponent [2R]. A highly simplified mathematical model is proposed for a numerical solution of the non-steady temperature distribution in solid propellant rocket motors [4R].

Laser-heated thrusters require protective cooling. It appears that the thruster walls can be protected by a combination of mass injection into the boundary layer and forced convection water cooling [5R].

General

Experiments [26S] on a *turbine* nozzle cascade established that the turbulence intensity of the approach flow (0.52–12%) may double the Nusselt number. Thin film gages were used [7S] to measure heat transfer to a gas turbine in a helium driven shock tube. An investigation was performed [25S] of heat transfer to turbine blades under transient operational conditions.

The heat-transfer resistance of slag and ash deposits on the panel walls of a *steam boiler* was measured [11S] with a water-cooled heat flow meter. Spectral absorptance and emissivity of ash and slag deposits are reported [13S, 14S]. The radiation heat transfer was measured [1S] on the tubes in the furnace exit of steam boilers including its circumferential distribution. A method of predicting the temperatures in the superheater of a drum boiler was discussed [22S] for the condition of accelerated start.

A simple model is proposed [16S] which predicts the effects of flow maldistribution on radial flow fixed bed *reactors*. Models describing the fuel-to-cladding heat-transfer coefficients in a reactor fuel element are reviewed [12S] and a new model is proposed.

A technique is presented [20S] which measures heat transfer in the cylinder of large *diesel engines*. Heat-transfer measurements were also performed during a single stroke piston compression [9S] and results of such measurements in a low RPM marine diesel engine have been reported [19S].

The following equation has been developed [18S] to describe natural convection heat transfer in horizontal annular cavities containing air

$$Nu_\delta = (0.181\,(r_o/r_i) - 0.215)\,Gr_{di}^{0.25}.$$

The ratio between the outer radius r_o and the inner radius r_i varied between 1.3 and 7.5. The Grashof number Gr varied between 3×10^3 and 10^8. The subscript δ stands for the difference in the two radii and the subscript di on the Grashof number indicates that this characteristic length is used. The heat transfer was minimized when the inner cylinder was moved somewhat upward from the concentric position. An internal layer of small permeability is proposed to improve the stability of the flow in evaporative cooling of a porous heat producing element [24S]. A new method [2S] is useful for the optimization of thermal insulation systems by minimizing thermodynamic irreversibility. Design data were established [23S] from experiments studying heat transfer from argon to helium II. A maximum heat flux of 1.7 W/cm^2 was observed at 1.91 K. The data should be useful for the design of superconducting magnetic energy storage. Temperature fields were studied [5S] in hybrid integrated circuits.

Computer calculations [3S] describe soil freezing by seasonally operating refrigerators. An idealized model is used [10S] to arrive at conclusions consistent with current practice on the response of building components to heating by a fire. Published data are correlated [15S] which describe heat transfer in agitated vessels containing single-phase Newtonian or non-Newtonian fluids.

Analysis and numerical solutions [8S] agree with plant observation on heat transfer in a ladle of molten steel during pouring. Thermocouples were used [6S] to measure dye temperatures during production drop forging. Equations are developed [21S] which describe convective heat transfer in rotary kilns with limestone and Ottawa sand. Air blowing out of the grinding wheel was found [17S] to effect the local heat-transfer coefficient and the temperature of the workpiece during the grinding process. A numerical solution of an alloy solidification problem was presented [4S].

Solar energy

Solar energy continued to be an active applications area. Topics of major interest among the heat-transfer related solar energy publications include: solar radiation; thermal properties of materials used in solar equipment; active collectors; passive collection techniques; and system performance.

Analytical expressions are presented which can be used to accurately calculate the direct and diffuse solar flux components using only the long-term daily-average total solar radiation on a horizontal surface [8T]. An atmospheric model has also been presented for computing direct and diffuse solar radiation [3T]. In a universal model, the direct solar transmittance of the sky is expressed in terms of fundamental measurable quantities [19T].

Studies of the radiation properties of materials used in solar collectors were reported in a number of papers. Calculations were used to demonstrate that in the 0.32–206 μm wavelength range, commonly used values of the reflectance of glass can be in error as much as 50% if the incident radiation is diffuse [16T]. Results are presented graphically for the transmittance of isotropic and non-isotropic diffuse radiation through one-, two-, and three-glass plates as a function of the position of the sun relative to the plate surface [23T]. Detailed calculations reaffirmed that the transmission of diffuse solar flux through a multi-plate glass cover configuration is accurately estimated using the transmittance of the cover system at an effective angle of incidence of 60° [21T]. A method of selected ordinates facilitates rapid determination of solar transmittance, absorptance, or reflectance with improved accuracy [38T]. An electrochemical conversion technique has been developed to deposit selective black nickel coatings (solar absorptance 0.94 and IR emittance 0.08) on galvanized iron and zincated or zinc-electroplated aluminum surfaces [15T]. An empirical relation was developed for the solar transmittance of a partially-absorbing mixture of water and Direct Black EX dye as a function of dye concentration and mixture depth [17T]. Suspensions of solid particles, of the appropriate diameter, in gases have been shown to have selective absorption properties [1T].

The performance of active solar collectors continues to be the dominant topic in the heat-transfer related solar energy literature. Based on the utilizability concept of Hottel, Whillier, Liu and Jordan, an analytical model has been developed to predict the long-term average energy delivered by almost any solar collector [9T, 10T]. Analysis has shown that steady-state salt-gradient solar ponds can be more efficient than common flat-plate collectors when the ratio of the difference between inlet and ambient temperatures to the incident solar flux is large [20T].

Flat-plate collectors were investigated both analytically and experimentally. The efficiency of a flat-plate collector whose absorber plate was fabricated from corrugated steel sheets was found to be somewhat lower than the efficiency of collectors fabricated with the more standard tube-in-sheet absorber plate [30T]. An examination of the radiant exchange for a collector with a tube-in-sheet absorber plate revealed that maximum collector efficiencies occur when the ratio of tube spacing to tube diameter is between 8 and 20 [32T]. The heat loss from a flat plate placed inside a partially-evacuated glass tube is approximately equal to that of a conventional flat-plate collector [25T]. Analysis shows that neither the use of honeycomb structures placed in the air gap between the absorber and cover plate to suppress free convection nor the evacuation of the air gap to eliminate conduction and free convection is as effective a method of improving collector performance as the use of selective surfaces [31T]. Neglecting axial conduction in the analysis of flat-plate collectors can result, for certain conditions, in over-predicting the heat transfer by up to 30% [22T]. The efficiency of a collector with the heat-transfer fluid undergoing phase change has been shown to increase linearly with the liquid level in the collector [33T]. Experimental results show that the wind-related heat-transfer coefficient on a flat-plate collector is greatest adjacent to the edges of the plate [34T].

A variety of concentrating solar collectors have been investigated. Vee-Trough/Vacuum Tube solar collectors were found to have efficiencies of 35–40% at an operating temperature of about 175°C [27T]. A permanently mounted (no-tilt adjustment) grooved collector appears to provide little benefit to the performance of a conventional flat-plate collector placed at the base of a groove [2T]. A high-temperature collector with a non-focusing Fresnel lens and a secondary concentrator has an efficiency of 48% for a solar flux level of 850 W/m^2 when the average fluid temperature is 200°C above the ambient temperature [7T]. Moderately-focusing heat-pipe solar collectors were found to have efficiencies comparable to typical flat-plate collectors [26T]. The effects of thermal optical design parameters on the performance of representative point-focusing solar power plants were assessed [36T]. Total heat losses from annular receiver geometries can be reduced up to 50% by varying the receiver dimensions and the gas pressure or composition in the annular space [24T].

Five papers reported studies on passive solar energy topics. A computer program for analyzing the performance of direct gain passive solar-heated enclosures accurately predicts the conditions of a test cell [35T]. Less than 10% difference was found between estimates of the solar fraction provided by a passive water wall solar system when analyzed using the *f*-chart and solar load ratio models [11T]. The performance of a passive solar heating system using a partially-transparent thermal storage wall was found to be approximately equal to direct gain or Trombe wall systems [13T]. A theoretical study of laminar free convection in one-dimensional solar-induced flows, similar to that which exists in many passive solar collectors, has been conducted [5T]. Experimental results were reported for a typical Israeli water heating system with thermosyphonic flow [29T].

A number of models for predicting the performance of active solar collection systems were proposed. A climatic design method has been presented which uses the long-term outdoor temperature distribution as well as the utilizability of solar radiation to predict the solar fraction for building heating [6T]. An algorithm was derived for choosing the insulation levels and the solar collection areas which will minimize the overall cost of constructing and heating a building [4T]. A Markov model approach to the generalized solar energy space heating performance analysis problem requires approximately 5% of the computer time required by other dynamic simulation approaches of comparable accuracy [18T]. An estimation of the fraction of a building heating load supplied by solar energy is made by approximating the heat storage, solar flux, temperature, and hot water demands by sinusoids and then solving the heat-transfer differential equations in closed form [12T].

An exact solutions approach for the analysis of a packed-bed thermal storage system appears to be more effective than the use of finite difference techniques [37T]. The use of thermal stratification in the sensible heat storage unit of a residential solar heating or cooling system can improve the overall system performance by up to 15% [28T]. The effect of buoyancy is greater on the local heat transfer than on the local mass transfer in a solar generator [14T].

PLASMA HEAT TRANSFER

Increased activities in the area of gas blast or vacuum arcs for circuit interruption and plasma processing are reflected by a relatively large number of papers in this section.

Measurements in an orifice-type air-blast model circuit breaker indicate that cooling depends much less on turbulence during the current zero process than predicted by turbulent theory [12U]. Studies of the flow situation in arc gas blast nozzles show that arc heating moves the sonic point a considerable distance downstream from the nozzle throat which may restrict the entire flow outside of the arc core to subsonic values [28U]. Diagnostic results for the thermal region surrounding the electrically conducting core of a gas-blast arc in a circuit-breaker model configuration should enable empirical laws to be derived as the basis for a boundary layer analysis of gas-blast arcs [31U].

A simplified arc model based on the integral method provides an adequate description of flow-dominated arcs in supersonic nozzles [9U]. A boundary layer integral method applied to a DC arc burning in a convergent–divergent nozzle of a gas-blast circuit breaker shows that for a given nozzle geometry the arc model predicts the current density at the nozzle throat where the mass flow approaches zero [6U]. Measured radial temperature profiles and electric fields in high-current (1–17kA), supersonic ($M = 1.5$) SF_6 interrupter arcs are used to evaluate axial and radial components of the energy balance. Axial losses may be as high as 75% of the input. A significant fraction of the input at 17 kA is lost by optically thin impurity (Cu) line radiation [2U]. A short magnetically driven arc in air produces an abrupt change in refractive index in the gas preceding the luminous region of the subsonic arc. The refractive index change is due to a front of high-pressure air sustained primarily by molecular heat conduction from the arc core [21U].

Although the cathode plays an essential role in the development of breakdown, the performance of a vacuum gap in terms of switching speed is much more affected by the material of the anode than that of the cathode[5U]. An improved model for anode spot formation in vacuum arcs shows that both magnetic constriction and anode evaporation must be taken into account [25U]. Measurements of the thermal balance of vacuum arc cathodes are in agreement with a previous theory for currents exceeding 100A [35U]. Erosion structures on cathodes arced in vacuum with currents up to a few hundred amps depend upon local conditions of energy input. The basic erosion pattern consists of craters ranging in diameter from less than 1 μm up to several μm [7U]. The application of a magnetic field of 0.35 T to a vacuum arc at 500A using Cu electrodes leads to an increased energy dissipation in the arc. The energy input to both electrodes increases with magnetic field strength, and the input to the anode is by a factor of 1.7 to 1.9 greater than the energy collected by the cathode [11U]. The formation of "hot spots" in a vacuum spark may be caused by electron beam heating of the plasma. It appears that the plasma pressure is $\geq 10^7$ atm and that the "hot spots" require heating rates $\geq 10^{15}$ W/cm^3 [23U]. Measurements in wall-stablilized arcs with superimposed axial flow demonstrate that the electric field strength increases with mass flow rate as turbulent effects become more pronounced [15U]. Employing a simple theory for the free-burning arc, predictions for arcs in air for currents ranging from 1 to 20 000A are in fair agreement with experiments for a position of 1 cm from the lower electrode [20U]. A simple model of metal–halide arcs has been used to assess the effects of adding different elements and mixtures of elements on the temperature profile and other properties of metal halide lamps [8U]. The improved color of the pulsed high-pressure sodium arc is due to the development of above steady-state plasma temperatures causing enhanced excitation of higher energy levels of sodium [18U]. The charged particle density in a cylindrical plasma boundary layer changes rather abruptly from "frozen" chemistry to thermochemical equilibrium in the neighborhood of the flow separation point [29U].

Studies of the anode region of high intensity arcs show that the electron enthalpy transport is the dominating heat transfer mechanism. The corresponding enthalpy flux may reach extremely high values if arc contraction occurs in front of the anode [19U]. Electrode erosion is one of the major reasons for the failure of high current sparkgaps used for switching. A new reliable sparkgap [130 kA, 0.7C] has been developed with electrodes consisting of a special type of graphite [1U]. Initial anode heat fluxes in pulsed high-current arcs may be an order of magnitude higher than the following quasi-steady heat fluxes [17U]. An arc operated in a flash tube at currents from 1 to 3 kA and with pulse lengths of approximately 1 ms interacts strongly with the enclosing tube. Oscillations of the luminous boundary and dark contractions of the arc channel have been observed [27U].

Calculations of the contribution of lines to the total emission coefficient of a thermal xenon plasma at temperatures between 10^4 and 1.4×10^4 K and pressures between 200 and 4000 kPa show the best agreement with measurements when a previously derived line factor is used [13U]. Radiation emitted from the axis of a wall-stablilized, low-current cylindrical arc in pure oxygen at temperatures around 9000 K and wavelengths from 2000 to 9000 Å consists primarily of contributions due to the affinity of the negative oxygen ions, the Kramers–Unsöld continuum and O_2^+ – association radiation [16U].

The gasdynamic and thermal parameters of non-isothermal, conventional plasma jets, both free and interacting with a baffle are studied experimentally. A semi-empirical relation derived for the stagnation-point heat flux on the baffle compares favorably with experimental results [4U]. An axisymmetric, supersonic ($M_2 = 2.32$), super-expanded, high temperature ($T \approx 3000$ K) gas jet impinges on permeable or impermeable surfaces arranged normal or inclined to the axis of the jet. If the heat-transfer intensifying effect of compression shocks is not taken into account, the error in calculating heat transfer may be as high as a factor of three [32U].

A numerical technique is described for determining the temperature distribution of a conical cathode in a MPD arc configuration [22U]. The glow-to-arc transition in a positive point-to-plane discharge can be explained by the Coulomb interaction heating process which arises whenever the collision frequency between electrons becomes greater than that between electrons and neutrals [3U]. A corona discharge gives rise to a large increase in heat transfer at low flow velocities and this gain in heat transfer decreases to zero at high stream velocities [30U].

Measured heat-transfer coefficients to stationary spheres of molybdenum (2–5.6 mm in diameter) in a confined argon plasma jet are in reasonable agreement with previous theoretical predictions [24U]. Numerical results for the heat transfer and phase change of spherical alumina particles heated in an argon–hydrogen plasma jet are in good agreement with measurements of surface temperature, particle velocity, and diameter [10U]. An experimental study of heat, mass, and charge transfer with chemical reactions on metal surfaces during transient heating with an argon plasma jet containing 4% oxygen, demonstrate that chemical reactions affect the heating of the metal, the convective heat transfer, and the transport of energy by radiation [33U].

Deviations from kinetic equilibrium (Te > Tg) in an argon plasma jet are diminished by mixing with nitrogen. The difference between electron and atom temperatures decreases with vaporization of metal particles injected into the plasma jet [34U]. Metallic particles with mean diameters as small as 0.005 mm may be produced by plasma jet heating of a porous graphite cylinder plated with the material from which the particles are generated [26U]. A multiple arc system capable of producing a large volume discharge may be useful for chemical and material processing in plasmas [14U].

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