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# HEAT TRANSFER—A REVIEW OF 1978 LITERATURE

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## INTRODUCTION

THIS review surveys results that have been published in various fields of heat transfer during 1978. 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 twenty-third Annual International Gas Turbine Conference was held 9–13 April 1978 at the Wembley Conference Centre, London, England. It included three sessions on heat transfer in which fifteen papers were presented on film and liquid cooling of turbine blades, cooling of disks, and on heat exchangers. The second AIAA/ASME Thermophysics and Heat Transfer Conference was in its greater part devoted to heat transfer. Papers may be obtained from the AIAA or from the ASME order department. Volumes on environmental effects of atmospheric heat/moisture release covering two sessions of the meeting can also be ordered from the ASME.

The twenty-sixth meeting of the Heat Transfer and Fluid Mechanics Institute was held at Washington State University 26–28 June 1978. About half of the papers presented were concerned with heat transfer problems. Three invitation lectures dealt with "Recent Trends in Experimental Heat Transfer and Fluid Mechanics" (A. E. Bergles), "Structure and Transport Properties in Turbulent Shear Flows" (L. S. G. Kovasznay), and "An Approach to Numerical Heat Transfer" (S. V. Patankar). The conference proceedings are available from Stanford University Press.

The Sixth Internation Heat Transfer Conference was held 7–11 August 1978 in Toronto, Canada. The Canadian Executive Committee chose a novel way for the organization of the conference by scheduling a large portion of the available time for discussion. The thirty-six keynote papers were presented by authors from many countries. They surveyed the present state of knowledge in the various fields of heat transfer, whereas the authors of the general papers were available to interested attendants for discussion of their papers during seventeen poster sessions, each covering ten to forty papers. Ten panel sessions were held on selected subjects. An exhibition of heat transfer equipment was open to attendants during the conference. The conference proceedings can be obtained from Hemisphere Publishing Corporation, Washington, DC in eight hardbound volumes.

The 1978 International Seminar, organized by the International Center for Heat and Mass Transfer, 1–5 September 1978, was devoted to two-phase momentum, heat and mass transfer in chemical processes and energy engineering systems. The conference proceedings are being published by the Hemisphere Publishing Corporation, Washington, DC.

The 1978 Annual Meeting of the American Underground Space Association was also held in Toronto, Canada, 21–23 October 1978. The presentations and discussions dealt primarily with energy demands of earth sheltered buildings. Information on the conference can be obtained through the American Underground Space Association, Department of Civil and Mineral Engineering, University of Minnesota. A Conference on Physicochemical Hydrodynamics, 6–8 November 1978 in Washington, DC, honored B. G. Levich. Twenty-five lectures discussed topics such as two-phase flow, change of phase, heat and mass transfer in chemical reactions, thermal diffusion effects and surface tension.

The Annual Meeting of the ASME, 10–15 December 1978, in San Francisco, included seventeen sessions devoted to heat transfer. Sessions on solar energy and gas turbines also included heat transfer effects. Chang-Lin Tien discussed heat transfer in the Peoples' Republic of China at the Heat Transfer Luncheon. Heat transfer memorial awards were presented to R. J. Goldstein and J. A. Clark. Dr. Benjamin Gebhart received the Freeman Scholar Award for his review of buoyancy introduced fluid motion characteristic of applications in technology. Reprints of the papers presented at the annual meeting are available at ASME Headquarters in New York and many of them will be published in the *Journal of Heat Trans*

A number of new journals deal with heat transfer subjects. The *Regional Journal of Energy, Heat and Mass Transfer* can be subscribed to at the Scientific Secretary, Regional Centre for Energy, Heat and Mass Transfer for Asia and the Pacific, Department of Mechanical Engineering, Indian Institute of Technology, Madras, India. The journal, *Numerical Heat Transfer*, started its publication in January 1978 and is available from Hemisphere Publishing Corporation and McGraw-Hill International Book Company. The journal, *Energy Developments in Japan*, started in July 1978 and can be subscribed to at Rumford Publishing Company, Chicago, Illinois. A number of books dealing with heat transfer or including heat transfer topics has appeared on the market. They are listed in the bibliographic part of this review.

Trends and developments in heat transfer research during 1978 are characterized by the following highlights: Studies in heat conduction included phase change and moving boundaries. Strong interest appeared in solution methodology. Channel flow was studied in complex configurations, and techniques to enhance heat transfer found attention. Also included were various types of fluid property effects, surface mass transfer and freezing.

Published work on boundary layers consists of experimental and numerical investigations. There is a greater emphasis on three-dimensional boundary layers, rough surfaces, stagnation point and conjugate heat transfer. Interest in heat transfer in separated regions on single bodies appears to be diminishing, whereas the literature on packed and fluidized bed heat transfer experienced an explosive growth.

The work on transfer mechanisms is almost exclusively concerned with turbulence. Detailed measurements of fluctuating quantities in shear flows have been reported. Statistical and phenomenological models for turbulent flows have been proposed. Natural convection studies concentrated on transient effects, non-Newtonian fluids and the use of finite element methods. Heat transfer from rotating single and multiple disks, in axially and radially rotating pipes and annuli was studied analytically and experimentally. Research on phase change appears to be reverting to fundamental analytic work.

Studies on radiative energy transport in non-gray emitting, absorbing, and scattering media are of particular interest. Results of measurements of radiation properties for various media have been published. Analysis is concerned with radiative exchange between surfaces including absorption, reflection, and polarization. The effect of scattering was studied in fibrous media. Papers concerned with measurement techniques concentrate on signal processing techniques to extract temperature and velocity information from hot wire measurements. Publications on the laser-Doppler method have decreased in number.

Interest in heat exchangers is still growing. Experiments are directed toward a detailed study of the performance of heat exchange surfaces using, for instance, the naphthalene sublimation technique. Analysis optimizes the performance of single heat exchangers and of arrays of them. Five papers investigate processes in heat pipes. Plasma heat transfer studies were primarily concerned with problems of arc circuit interruption and with applications in plasma chemistry.

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
  Surface radiation, L
Measurement techniques, P
Heat-transfer applications
  Heat exchangers and heat pipes, Q
  Aircraft and space vehicles, R
  General, S
  Solar energy, T
Plasma heat transfer, U.

## CONDUCTION

The recent heat conduction literature is dominated by phase change and related moving boundary problems. There is, in addition, a strong interest in solution methodologies.

The basic assumption that Stefan-type melting problems are purely heat conduction problems was severely shaken by recent experiments. Those experiments, which involved a horizontal cylindrical heater embedded in a phase change medium, demonstrated that after a brief initial period when conduction prevails, the melting process is dominated by natural convection in the liquid melt [42A]. A similar finding was encountered in experiments in which the melting occurred about a vertical cylindrical heater [35A]. Experiments on the freezing of water passing in crossflow over a cooled tube showed that the thickness of the frozen layer is a minimum at the forward stagnation point and increases around the circumference, attaining a constant value in the rear portion of the cylinder [30A]. An analysis of solidification in a continuous casting process showed that the thickness of the solidified material increases approximately as the square root of the distance along the mold from the location where solidification begins [39A]. Increasing the ingot withdrawal rate or the heat addition at the solidification surface causes the interface to move downward within the mold and have a nonplanar shape [40A]. A metal sphere, when immersed in its own liquid, will at first be enveloped in a freezing annulus which will subsequently melt, as will the sphere itself [10A]. A numerical solution for simultaneous melting and evaporation was motivated by the need to determine the propagation of the melting crater and the material erosion in electrical discharge machining [50A]. The inward freezing in an annulus was found to be markedly influenced by the thermal boundary condition at the inner bounding cylinder [16A].

A novel numerical approach, which focuses on the melting (freezing) of particles rather than of the bulk solid, has been formulated and applied [13A]. Another innovative numerical scheme for one-dimensional phase change problems continuously follows the position of the moving interface [12A]. To neutralize the difficulties of dealing with a moving boundary in phase change problems, a change of variable has been introduced which fixes the melting (freezing) front [38A]. To facilitate an analysis of the melting of a subcooled solid surrounding a heated cylinder, coordinate transformations were made which immobilize both the moving interface between the melt region and the solid and the moving temperature wave that diffuses into the solid. Depending on the degree of subcooling, the surface heat transfer can be several times greater than that for no subcooling [41A]. The application of the enthalpy method to multidimensional phase change problems is once again described, thereby repeating earlier work published in the *Journal of Heat Transfer* **97**, 333 (1975) [9A]. In a finite-element method, the difficulty of handling sharp peaks in the heat capacity–temperature curve has been mitigated by use of the enthalpy as the prime variable, with the specific heat being evaluated as a simple backward difference involving enthalpies and temperatures [27A]. For substances which solidify over a range of temperatures, an analytical method which uses an apparent heat capacity which includes the latent heat was proposed and evaluated experimentally [14A]. A refinement of the Heat Balance Integral for phase change problems is based on subdividing the surface-to-melting (freezing) temperature range into equal intervals and applying the HBI to each individual interval [4A].

The liberation (or absorption) of heat during solidification (or melting) can be treated as a moving heat source (or sink) located at the liquid–solid interface [31A]. The Landau melting problem, which is characterized by an applied heat flux at the moving interface, was numerically solved by working with an integrodifferential equation for the position of the interface [36A]. Solidification of a binary mixture of finite thickness does not admit an exact solution, and a series method has been used [5A]. A generalized Neumann problem involving arbitrary initial conditions and arbitrary boundary conditions does not yield a similarity solution as do the basic Stefan and Neumann problems, but the similarity variable $x/\sqrt{t}$ can be used in constructing the solution for the generalized problem[46A]. The zero- and finite-order moments of the heat equation, used in conjunction with physically motivated inequalities relating to the temperature distribution, were employed to determine bounds on the movement of the interface in Stefan-type problems [11A]. A moving boundary problem with combustion at the moving interface was studied from the existence-uniqueness viewpoint, but useful solutions are not presented [44A]. The governing equations and solution algorithm for one-dimensional transient heat conduction in an expanding rod with one free end are similar to those for Stefan-type phase change problems [24A].

Several papers dealing with topics in steady heat conduction have been published. The critical radius of insulation has been generalized to accommodate experimental correlations of the natural convection heat transfer coefficient which account for variations of temperature difference and body dimensions [3A]. A further generalization included the effects of uniform surface heat generation due to a phase change at the external convection boundary [19A]. A new algorithm has been formulated for evaluating the performance of arrays of extended surfaces: the performance of the array involves cascading the parameters for the individual fins [17A]. Exact (series) solutions were derived for the steady state temperature field in an infinitely long cylinder in which there is a non-axisymmetric heat source [29A]. A series method was used for determining the steady temperature field in an eccentric annulus with uniform inner thermal conditions and circumferentially nonuniform outer conditions [2A]. Solutions were obtained via Green's functions for the steady temperature field in a nonmoving liquid metal contained in a long duct in which there is a heated centerbody of finite length [25A]. The Picard iterative technique is shown to be effective in solving steady one-dimensional heat conduction problems with internal heat sources [26A]. In the conduction limit (zero Reynolds number) for the Nusselt number for flow external to bodies, the effect of variable thermal conductivity in the fluid is independent of the shape of the body [7A].

Transient problems were treated in a number of papers. The orthogonal collocation method, as applied to transient heat conduction with variable conductivity, involves the approximation of the spatial derivative terms in the energy equation by an orthogonal polynomial, thereby transforming the equation into a set of ordinary differential equations that can be integrated numerically [20A]. Temperature-dependent thermal conductivity in transient conduction problems can also be handled by a series solution in which the expansion parameter is related to the conductivity variation [45A]. Correction formulae have been developed to extend the applicability of the Heisler transient response charts to solids with temperature-dependent thermal conductivity [43A]. The use of a vectored separation of variables approach enables solution of the coupled partial differential equations which express energy conservation for the fluid and solid components of a packed-bed thermal storage tank [22A]. The temperature field created by a moving three-dimensional heat source was determined by integration of a solution for a one-dimensional source [49A]. Upper and lower bounds on the transient temperature distribution in the region surrounding a buried cylindrical heat source were determined by application of the theory of differential inequalities [23A].

Interest persists in composite and anisotropic solids. A mixture theory for diffusion in a fiber-reinforced composite converts what is essentially a three-dimensional problem into a problem involving a single spatial variable [21A]. In another paper, it was shown that a number of anisotropic heat conduction problems can be transformed into isotropic ones [33A]. The idea of using steady equivalent thermal properties as an alternative to unsteady heat conduction analysis was experimentally examined for layered composites and found to be satisfactory only when the thermal conductivities of the two constituents do not differ widely [48A]. An analysis of the transient temperature field in an aerodynamically heated laminated composite conical shell utilized Galerkin's method in conjunction with the Laplace transform technique and showed that the resulting temperature gradients were large enough to warrant concern about thermal stresses [34A]. The heat propagation in bilaminates depends critically on the behavior at the interfaces [15A]. A steady state solution for an infinite anisotropic sheet surrounding an insulated elliptical hole indicates the presence of rapid temperature changes adjacent to the hole [37A].

Numerical methods have already been cited in earlier paragraphs of this section, and other numerically oriented papers will now be reported. Computationally useful methods have been devised for determining the critical time step to prevent oscillatory results in a finite-element marching solution for two-dimensional transient heat conduction [28A]. A finite-element procedure for elements with several temperature-dependent thermal parameters was formulated by resolving element matrices into component matrices, one component for each thermal parameter [47A]. Through examples, it was demonstrated that a finite-element method can be effectively used to treat the inverse problem of transient heat conduction [18A]. In a novel approach to the solution of transient heat flow problems in two dimensions, the movements of isotherms along orthogonal lines are treated in successive small intervals of time [8A]. The use of a Galilean transformation to immobilize a moving thermal interface leads to a finite element method where the element stiffness is no longer symmetric [32A].

There are a few rather mathematical papers which deal with topics of engineering relevance. Mathematical theorems are employed to devise a method for determining the thermal conductivity from overspecified initial and boundary data [6A]. Some progress has been made toward formulating the problem of heat conduction in the presence of random thermal conductivity, but neither numerical solutions nor results have been obtained [1A].

## CHANNEL FLOW

The current literature on heat transfer in ducts reflects a strong interest in flows in complex configurations and in techniques to enhance heat transfer. Various types of fluid property effects, including non-Newtonian behavior, were investigated. A modest interest in turbulence models persists, and a number of papers concerned with mass transfer and with freezing have been published. The venerable area of laminar developing and fully developed heat transfer continues to draw some attention. On the basis of a new compilation of data, the exponent of the Reynolds number in a Nusselt–Reynolds–Prandtl correction for turbulent pipe flow has been shown to be a function of both Re and Pr, for Prandtl numbers below 100 [15B].

Research involving complex flows and enhanced heat transfer surfaces will now be described. Augmentation is accomplished in a static mixer by alternately subdividing the flow into separate parallel streams and then recombining the streams [60B]. A finite difference solution for turbulent heat transfer in a wavy-wall tube shows that positive results of the augmentation can be attained at moderate and small Pr, but not at large Pr [25B]. The use of sonic oscillations to increase laminar and turbulent heat transfer in a tube may have a side benefit of preventing salt deposits on heat transfer surfaces in commercial heat exchangers [51B]. Turbulent airflow experiments in a parallel plate channel with rib-roughened surfaces showed that ribs at a 45° angle of attack have superior heat transfer performance at a given friction power than ribs at a 90° angle of attack or than sand-grain roughness [26B]. For a two-plate colinear array aligned parallel to the flow, airflow experiments showed that under most practical considerations the effect of increasing plate thickness is to increase the Nusselt number [16B].

Measurements of heat transfer in an array of wall-attached cylinders situated in a crossflow of air in a flat rectangular duct showed that fully developed conditions prevail for the fourth and all subsequent rows [56B]. Experimentally determined heat transfer coefficients on the upstream and downstream faces of a transversely positioned blockage in a square duct were found to be quite insensitive to the extent of the blockage [57B]. Heat transfer experiments in helical coiled tubes showed that the overall heat transfer coefficients are relatively insensitive to whether the boundary condition is uniform wall temperature or uniform heat transfer per unit length [31B]. Heat transfer results for fully developed laminar flow in a pipe containing a longitudinal rod assembly were found to be sensitive to the size of the gap between the outermost ring of rods and the pipe wall [4B]. A new form of Reynolds analogy for a rough surface, derived on the assumption that the eddy Prandtl number is constant, is purported to supersede existing relationships [38B].

When a tube or duct flow is subjected to a streamwise periodic variation of wall temperature or wall heat flux, a periodic thermally developed regime is established at sufficient distances from the inlet [44B]. An analysis of laminar forced convection heat transfer from a shrouded fin array with tip clearance shows that the minimum fin heat loss occurs adjacent to the fin base and the maximum heat loss occurs at the tip [54B]. In turbulent duct flows in which the walls are nonuniformly heated and in which wall conduction plays a role, the Reynolds number exponent in the Nusselt–Reynolds relation is modified by the interaction of the wall conduction with the fluid convection [5B]. For pipe flow experiments involving circumferentially varying thermal boundary conditions, criteria are formulated which facilitate the determination of boundary conditions on the inner wall of the tube from measurements made on the outer wall [3B].

A strong interest has been evidenced in various types of fluid property effects. An analysis of the effects of temperature-dependent viscosity on fully developed turbulent pipe flow for liquids expresses the heat transfer coefficient ratio for variable to constant viscosity in terms of the friction factor ratio for variable to constant viscosity as well as of the wall and bulk temperatures and of a fluid viscosity–temperature parameter [27B]. An experimental investigation of heat transfer to laminar flow of oil in a horizontal pipe gave results which agree with the Sieder–Tate correlation at small temperature differences, but deviate at larger temperature differences [42B]. The accounting of variable liquid viscosity in laminar pipe flow shows that the Nusselt number is increased by heating and decreased by cooling [35B]. A linear stability analysis studying the onset of secondary flows in a parallel plate channel dealt with water in a temperature range which encompassed the maximum density condition [13B]. The transient response of a turbulent supercritical water flow in a tube is different for increases of wall heat flux than for decreases in wall heat flux [53B]. The correlation of heat transfer data for supercritical helium is facilitated by a harmonic mean Prandtl number and the use of a Reynolds number which is the lesser of the Reynolds numbers corresponding to wall and bulk conditions [8B]. The turbulent friction and heat transfer coefficients for dilute suspensions of asbestos fibers in water may be much lower than those for water flow alone [41B]. Analysis and experiments for electrorheological laminar flow in an annulus showed that the heat transfer is enhanced with increasing electric intensity [52B]. When the Joule–Thompson effect is important, the pressure work and viscous dissipation have to be included in the energy equation, as in an analysis of the turbulent Graetz problem [11B].

The interest in property effects is further substantiated by research on non-Newtonian flows. From numerical solutions for simultaneously developing flow and heat transfer in a square duct, it is found that for the same Graetz number, Prandtl number, and thermal boundary condition, a non-Newtonian fluid with flow behavior index $<1$ gives a higher heat transfer coefficient than a Newtonian fluid [9B]. Correction factors have been formulated to relate temperature-dependent dissipative non-Newtonian flows to simpler flows where these effects are absent [62B]. A study of the thermal entrance region for combined Couette–Poisseuille flow of a power-law non-Newtonian fluid showed that dilatant fluids attain developed temperature profiles in shorter lengths than do pseudoplastic fluids [39B]. Numerical solutions enabled correlation of variable property effects for laminar non-Newtonian flow in a tube with uniform wall temperature [24B]; the uniform heat flux case is treated in a companion paper [23B].

A few papers deal with turbulent transport characteristics. The fully developed heat transfer for turbulent flow in concentric annuli, for which prior solutions have been obtained by eddy diffusivity models, was resolved by employing a surface rejuvenation model [14B]. Best agreement of analysis and experiment for radial and circumferential diffusion in turbulent flow in an annulus occurs for a ratio of circumferential to radial eddy diffusivity equal to two [28B]. Experiments on turbulent airflow in the entrance region of an isothermal-walled tube gave a value of 0.97 for the turbulent Prandtl number in the turbulent part of the wall region [29B]. A penetration model for the fluid boundary layer adjacent to a pipe wall enabled calculation of the effect of chemical reaction on the heat transfer coefficient for turbulent pipe flow [43B].

Mass transfer effects drew some attention. Injection of fluid at the inner wall of an annular duct leads to an increase in the turbulent heat transfer coefficient corresponding to heating at the outer wall [19B]. Laminar flow in a parallel plate channel with injection of a reactant was studied to aid in interpreting experiments on diffusion flames in counterflow configurations above liquid and solid fuels [50B]. The axial heat conduction problem for laminar pipe flow has been re-examined in the context of mass transfer [17B]. Fully developed heat transfer in a tube in the presence of an external thermal resistance was revisited in the analogous problem of mass transfer with a first-order chemical reaction at a catalytic wall [30B]. Mass transfer measurements for turbulent airflow in an annulus with non-axisymmetric injection of nitrous oxide gas at the outer wall demonstrated that an isotropic eddy diffusivity model underestimates the magnitude of the circumferential diffusion [48B]. The Leveque solution, which is valid in the immediate neighborhood of a duct inlet, has been extended to larger downstream distances for laminar flow in a parallel plate channel in which the wall mass (heat) flux is proportional to the wall concentration (temperature) [10B].

The freezing of liquids in pipes was investigated. Experiments on the freezing of water flowing turbulently in a cooled isothermal tube agreed well with analytical predictions based on a simple turbulence model [59B]. In the flow of hot Freon 112A through a melting ice pipe, two distinct modes of Freon freezing were observed [63B]. Previous solutions for solidification in a tube having a given wall temperature were extended to the case where there is a convective heat transfer to a fluid environment outside the tube [20B]. The classical Graetz-type analysis was extended to the case of laminar liquid flow in a parallel plate channel in which there is sufficient cooling at one of the walls to cause freezing at that wall [12B].

Papers on laminar duct flows continue to appear. In a pair of companion papers, the Galerkin–Kantorowich variational method was used to solve the laminar thermal entrance region problem for a rectangular duct and a circular tube, the outside surface of which exchanges heat with a surrounding fluid medium; the tube study also took MHD effects into account [32B, 33B]. Finite difference and Galerkin solutions for the laminar thermal entrance region of an annulus agree very well with each other [40B]. A series solution starting at the pipe inlet and proceeding in the downstream direction was used for solving the laminar entrance region problem for a variety of thermal boundary conditions [47B]. A refined integral momentum and energy analysis for simultaneously developing laminar velocity and temperature in a parallel-plate channel gave Nusselt numbers that are in good agreement with literature values [6B]. Heat transfer measurements in the entrance region of a rectangular channel with laminar or transitional flow of air resulted in a correlation [36B]. Circumferentially nonuniform heating in the entrance region of a laminar pipe flow cannot be handled by the methods used in the Graetz problem because the eigenfunctions are not orthogonal [21B]. In the thermally developed regime for laminar pipe flow where there is heat exchange with the surroundings via a circumferentially varying external heat transfer coefficient, the average heat transfer coefficient is quite insensitive to the imposed circumferential variations [55B].

A variety of topics are treated in papers published in *Heat Transfer, Soviet Research*. These include: transient heat transfer in tube flows [34B, 49B], variable property effects [1B, 61B], effect of turbulence level in the fluid entering a tube or duct [18B, 58B], axial wall temperature variations [45B], high frequency pressure fluctuations [22B], crossflow heat transfer to a flattened tube situated in a duct inlet [2B], high Prandtl number experiments using electrochemical techniques [7B], deviations from Reynolds analogy due to surface roughness [46B], and longitudinal turbulent flow in a rod bundle [37B].

## BOUNDARY LAYER AND EXTERNAL FLOWS

Publications on boundary layers deal with laminar and turbulent flows on flat and curved surfaces, flows over cylinders and spheres, free jets, impinging jets, and falling liquid films. Some new experimental data have been presented, and a considerable amount of activity has been directed towards the development and application of analytical and numerical techniques.

A calculation method has been reported for the analysis of two-dimensional boundary layers [5C]. For the same general situation, a Galerkin finite-element method using Hermitian polynomials has been applied, and the results have been compared with those from other methods [6C]. A new numerical solution scheme is described for the multi-equation systems encountered in local nonsimilarity boundary layer analysis. It employs integrated forms of the governing equations, which already satisfy the boundary conditions. The method is shown to be very efficient compared with the usual forward integration/shooting method [40C]. A numerical scheme is presented for boundary layers with massive injection through a porous surface. It is based on the exponential difference operator and on the general approach of the Keller box scheme. Applications were made to self-similar boundary layers [14C]. A calculation method which is capable of handling regions of sharp pressure gradients in two-dimensional laminar boundary layers is described [11C]. Calculations are reported for turbulent compressible boundary layers on a permeable plate [3C]. An integral method has been used to predict friction and heat transfer from compressible turbulent boundary layers in a convergent–divergent nozzle. The predicted results are shown to agree well with experimental data [35C]. An integral analysis of the thermal turbulent boundary layer is described; it uses the inner region parameters based on the friction velocity [58C].

Three-dimensional turbulent boundary layers have been computed by a finite-difference method, the turbulence being characterized by a two-equation model. The situations chosen for the computation are: the boundary layer on a flat plate approaching a circular cylinder mounted on the plate, the boundary layer beneath the leading-edge vortex on a delta wing, and the flow near the upper surface of a curved duct. The predicted results show reasonable agreement with available experimental data [45C]. A three-dimensional parabolic procedure employing non-orthogonal coordinates has been developed for the prediction of turbulent boundary layers on bodies of arbitrary shape [34C].

The second-order laminar boundary layer over a parabola has been analyzed [21C]. The Reynolds analogy is discussed with reference to boundary layers with pressure gradients [39C]. Squire's temperature profile for a turbulent boundary layer on an adiabatic flat plate has been extended to the case of finite heat transfer. The Reynolds analogy factor has thereby been deduced, and the results have been compared with experimental data [60C]. A transport equation for the turbulent heat flux in a boundary layer has been derived on the basis of local similarity [2C]. The diffusion in a turbulent boundary layer downstream of a line source is discussed. Two different eddy diffusivity distributions are considered, and their implications are compared with experimental data [37C].

An analysis has been made of turbulent boundary layers subjected to adverse pressure gradients. A general family of velocity profiles was derived from the assumption that the boundary layer is in local equilibrium. The family agrees well with almost all available experimental data [23C]. Solutions have been presented for the boundary layer equations with prescribed variations of the free-stream velocity. The method of inner and outer expansions is used [38C]. An approximate analysis has been reported for the thermal response of a laminar boundary layer over a smooth object of arbitrary shape. The results show good agreement with available experimental data for Prandtl numbers of unity or larger [31C]. Dimensionless equations are given for laminar flow heat transfer with variable physical properties [33C].

Some work has dealt with boundary layers on rough walls. An algebraic eddy–viscosity model modified for wall roughness has been used to predict turbulent boundary layers in adverse, zero, and favorable pressure gradients. The results show satisfactory agreement with experimental data [8C]. A method is described for the calculation of heat transfer from rough surfaces [54C]. An integral method has been developed for the prediction of heat transfer from a fully rough turbulent boundary layer. The predictions show good agreement with experimental data over a range of conditions including variations of free-stream velocity, surface temperature, and blowing [10C].

Some new analytical results are presented for conjugate heat transfer in a flat plate boundary layer [25C]. For the same problem, an approximate method for solving an integral equation is described [26C].

The results of numerical calculations are reported for turbulent boundary layers with significant variations of physical properties [56C]. A companion experimental investigation presents results for the heat transfer rates in a channel through which combustion products flow [12C].

The problem of heat/mass transfer to a finite strip at low Peclet numbers was solved by the method of matched asymptotic expansions. Experimental data obtained by the limiting-current method show excellent agreement with the theoretical predictions [1C].

Among other experimental investigations, heat transfer measurements were performed in a two-dimensional convergent–divergent nozzle. In the cooled boundary layer with increasing favorable pressure gradient, the heat transfer was found to decrease when the dissipation was small, and to increase when the dissipation was large [61C]. An investigation is reported of the mean and fluctuating characteristics of the thermal turbulent boundary layers in divergent flows [30C]. Measurements have been made of the mean-flow profiles in a turbulent boundary layer at a Mach number of three for various wall-to-total temperature ratios [29C]. The effect of an upstream adiabatic zone on the heat transfer in the downstream boundary layer has been investigated [41C]. The local and average rates of mass transfer have been determined for thick plates placed in parallel flow [27C]. An experimental investigation is reported for the laminar flow in a rectangular streamwise corner [13C]. Experiments have been performed on a free turbulent jet, in which the mean fluxes of mass, momentum and total enthalpy were measured. An extension of the Reichardt inductive theory is used to adequately predict the measured quantities [50C].

Measurements in high-Reynolds-number boundary layers have shown that the effect of free-stream turbulence is to increase heat transfer by about 5% for each 1% rms increase of the longitudinal intensity [52C]. The effect of free-stream turbulence on the heat transfer to curved surfaces has been investigated [7C].

Other studies related to curved surfaces include the use of second-order boundary layer theory to determine the influence of the Prandtl number on the heat transfer at the stagnation point [17C]. Also, the governing equations for a supersonic turbulent boundary layer over a wavy surface have been solved numerically. The eddy–viscosity model of Cebeci and Smith has been used, and the predictions are compared with experimental data [44C].

Flow over cylinders and spheres is the topic of a number of papers. An integral analysis of the thermal boundary layer on a continuous cylinder travelling through stagnant ambient fluid has been reported [24C]. Laminar forced convection from non-isothermal thin needles was analytically investigated, in which similarity temperature fields have been obtained [9C]. An analysis has been made of the effect of suction and slip velocity of a non-Newtonian fluid flowing over a circular cylinder [47C]. A series method has been used to analyze the thermal boundary layer on an isothermal cylinder in cross flow of a micropolar fluid [36C]. Boundary layer solutions are presented for the effect of viscous dissipation on the steady-state heat transfer in an axisymmetric stagnation flow on an infinite cylinder. The boundary conditions of isothermal and adiabatic wall have been treated for a wide range of the Prandtl number [18C]. Experimental data are reported for local heat transfer rates from a cylinder undergoing transverse oscillations while being subjected to a cross flow. Local heat transfer coefficients were found to increase up to 60% [46C]. The local heat transfer from a sphere in a turbulent flow has been experimentally investigated for Reynolds numbers ranging from 2600 to 6100 [20C]. An analysis has been made of the heat transfer from a porous sphere in a low Reynolds number flow [55C]. Also, the creeping flow around a sphere has been analyzed [48C].

Numerical studies of impinging jets are reported. An analysis has been made of the heat transfer from a laminar water jet impinging on a surface. The potential flow region was solved by a finite-element method, while the boundary layer problem was solved by an integral method. The solutions include the effect of melting at the impingement surface [32C]. The heat and mass transfer to a surface from a laminar impinging jet has been calculated by a finite-difference method. The effect of initial jet velocity profile has been investigated [15C].

Some work has been associated with unsteady boundary layers. Finite-difference solutions have been obtained for the unsteady laminar boundary layer flow at a three-dimensional stagnation point. The velocity of the incident stream is taken to vary arbitrarily with time [28C, 43C]. A method is described for solving laminar boundary layer equations with periodic fluctuations of the outer-flow velocity and temperature. The method combines numerical analysis and perturbation techniques and leads to a significant reduction of computer storage [57C]. Two examples of nonseparating unsteady boundary layers with local flow reversal have been constructed from semi-similar solutions. The associated thermal boundary layers imply no drastic change of heat transfer at the locations of flow reversal [59C]. A simple analysis has been presented for unsteady heat transfer in impulsive Falkner–Skan flows. The results are compared with those from an earlier numerical solution [19C]. An analytical investigation deals with the flow and heat transfer along a porous plate subjected to a transverse sinusoidal suction velocity distribution fluctuating with time [53C]. Experimental data are reported for the augmentation of convective heat transfer by mechanical scraping of a surface boundary layer [22C].

Heat transfer from liquid films continues to be a topic of research interest. The local transfer rates between a liquid film and a horizontal tube have been measured by an electrochemical technique. The transfer rate was found to depend on the mode of liquid feeding [51C]. An exact solution of the convective diffusion equation for the case of dissolution of a solid wall into a falling laminar liquid film has been obtained. The results show satisfactory agreement with experimental data for the dissolution of gypsum into water [4C]. Existing data for the transport to falling liquid films are reviewed to show the effect of augmented transport by surface waves [49C]. An analysis has been made of the heat transfer to a non-Newtonian laminar falling liquid film on an inclined wall [42C]. The influence of heat transfer and interfacial shear on the hydrodynamic stability of thin liquid films has been analyzed. The linear stability of the flow is determined by a successive perturbation solution of the governing Orr–Sommerfeld equation [62C]. An experimental study is reported for the heat transfer coefficient and film breakdown heat flux in subcooled water films flowing down on the outside of a heated vertical tube [16C].

## FLOW WITH SEPARATED REGIONS

### Single bodies

Transfer coefficients on both surfaces of a blockage plate situated in a duct flow are insensitive to the extent of the blockage [20D]. The $k$–$\varepsilon$ turbulence model is used to predict successfully the recirculating flow in a cylindrical enclosure [18D]. Williams [21D] discusses the nature of unsteady three-dimensional laminar separation. Two papers by Simpson and Collins [6D, 19D] deal with flowfield predictions of separating turbulent shear layers. A numerical scheme is given [16D] for the simultaneous solution of a boundary layer and an outer inviscid stream with separated flow. LaRue and Libby [14D] deal with detailed similarity in the turbulent wake of a heated cylinder.

### Packed and fluidized beds

Interesting details on visualization of blob mechanics in flow through transparent porous media are given in [17D]. Natural convection experiments in rectangular cavities packed with porous media revealed [9D] that Prandtl number and aspect ratio have significant effects on the heat transfer. In a theoretical model of heat transfer to a packed or quiescent fluidized bed [5D], the bed is divided into two regions of constant bed voidage and gas velocity. The low Peclet number behavior of the Sherwood number in a packed bed is dependent upon its defining equation [8D]. A recently developed variational principle of virtual dissipation was applied [4D] to coupled heat and mass transfer in a porous solid containing a fluid.

The basis for a method for estimating the effective radial thermal conductivity of packings in gas flow [2D, 3D] is the sum of a convective fraction and a packing fraction through which the gas does not flow but includes conduction, radiation, and the Smoluchowski effect. Another analysis [11D] deals with the effective shear viscosity of a regular array of suspended spheres. Experimental measurements of particles in fixed beds show [10D] either a constant Nusselt number as the Reynolds number is reduced or, if axial dispersion is neglected, the Nusselt number decreases to zero. Literature correlations for predicting axial mass dispersion coefficients [13D] may lead to adequate accuracy in technical equipment, but analyses of packed bed processes in a laboratory or bench scale study should include separate investigations of dispersion behavior. An extensive review of heat transfer in porous media is given in [15D]. Transient heat transfer in liquid flow through permeable subsurface strata is described [12D]. The surface tension of the liquid was shown to be an important variable in mechanically agitated gas-liquid dispersions in a helical coil [7D]. A design equation is given for gas-to-particle heat transfer in vertical pneumatic conveying of granular materials [1D].

## TRANSFER MECHANISMS

Detailed measurements of turbulent flows and formulation of mathematical models for turbulent transport have been the main research activities in transfer mechanisms.

An experimental study has been made of the decay of temperature fluctuations in grid-generated turbulence. The decay rate was found to be a function of the initial temperature fluctuation intensity [27E]. Another experimental investigation showed that the magnitude of the skewness of the temperature derivative in a turbulent flow downstream of a heated grid is small and can be reduced to zero by perturbing the flow with a second ambient temperature grid [3E]. Measurements are reported for the turbulence produced by a grid which simultaneously provides a mean temperature profile varying linearly with height. The downstream evolution of the temperature fluctuations was found to disagree with an earlier theory; the discrepancy is attributed to the neglect of molecular diffusivity [26E].

Detailed turbulence measurements are reported in heated turbulent jets and mixing layers [21E, 22E]. Structure functions of turbulent temperature and velocity fluctuations have been measured in the atmosphere and in the laboratory. The laboratory measurements were performed for the inner region of a thermal boundary layer and on the axis of a heated jet [5E]. Both conventional and conditional measurements for the temperature and velocity fields in a round heated turbulent jet are reported. The measurements show that the large-scale turbulent motions are responsible for the bulk of momentum and heat transfer and that small scales are more efficient in transporting heat than momentum [9E]. Correlation measurements were made in both broad and narrow frequency bands of the longitudinal velocity fluctuations in fully developed pipe flow. The data show that the low-frequency, large-scale fluctuations extend over most of the radial region and are highly correlated [8E]. The mean velocity field and the six components of the Reynolds stress tensor were measured in a three-dimensional turbulent boundary layer with moderate skewing relative to the free-stream direction. The stresses were measured by a rotating probe technique [11E].

Calculations are reported for the turbulent heat transfer in a stabilized pipe flow [18E]. A model is described for the prediction of turbulent heat transfer in gas-liquid flows [20E]. From the statistical characteristics of turbulence, calculations have been performed for the convective heat transfer in turbulent flow [10E]. A method is described for the prediction of turbulent shear flows in which non-equilibrium chemical reactions take place [13E]. A numerical method has been formulated for the solution of turbulent flow problems [30E]. The algebraic stress modeling technique has been applied to the prediction of a round turbulent buoyant jet. Transport equations were solved for the turbulence kinetic energy, its dissipation, and the mean square temperature fluctuations [23E]. Numerical solutions have been presented for compressible boundary layers. An integral form of the equation for the turbulence kinetic energy is employed. The results are obtained for relaminarization, various pressure gradients, and surface roughness, and are compared with experimental data [1E].

A theoretical discussion deals with the role of the Prandtl number in turbulent flow. A simple model based on spectral considerations has been used to obtain an approximate solution [19E]. A periodic intermittent model has been developed for the wall region of a turbulent boundary layer. The model accounts for the intermittent bursts and the longer viscous flow that prevails between the bursts [25E]. A phenomenological model of intermittency has been presented. It employs dynamical quantities such as velocity amplitudes, eddy turnover times and energy transfer [12E]. The properties of constitutive heat transfer equations for materials with memory have been derived from thermodynamic restrictions. A number of inequalities have been obtained for restricting the behavior of the constitutive equations [15E].

A theoretical procedure is described for the interline heat transfer at the junction of liquid–solid–vapor. The analysis assumes that the interline transport is controlled by the London–van der Waals dispersion force between the condensed phases (solid and liquid) [29E]. The heat sink capability of the interline region has been determined by an approximate procedure which includes the effect of the solid resistance to heat transfer. The limiting case in which the solid conductivity is the controlling factor is given primary attention [28E].

The influence of buoyancy on turbulent transport is discussed with reference to a transport model derived from the application of the eddy-damped quasi-Gaussian approximation to the equations for the third moments. The model requires that a flux of one quantity depends on the gradients of all relevant quantities [17E]. Some correlations among turbulent shear stress, kinetic energy of turbulence and axial turbulence intensity have been developed by reference to experimental data for pipe and channel flows [2E]. The surface renewal model has been employed to formulate expressions for the eddy viscosity and the eddy diffusivity [24E].

A stochastic model has been proposed for the calculation of turbulent diffusion [16E]. A theoretical discussion deals with the accuracy of the structure function of temperature in turbulent shear flows [4E]. A number of experimental studies of wall turbulence have been re-examined to evaluate the ratio of the time scale of a scalar-fluctuation field to that of the velocity-fluctuation field. The ratio was found to be nearly uniform and equal to about 0.5 [6E]. A quantitative model is described for the momentum transfer by coherent motion in turbulent boundary layers. The large-scale eddies are supposed to synchronize with the bursts near the wall. The results show reasonable agreement with experimental data [7E]. A system of linear equations are presented for the determination of the fields of velocity and of a general scalar variable in a turbulent flow. The system characterizes the large-scale coherent structures found experimentally in turbulent flow [14E].

## NATURAL CONVECTION

Publications on convective heat transfer in which buoyancy plays a major role in determining the fluid motion appear to be unbounded. As has been true for some time, there is active interest in boundary layer flows, flow in enclosures, and combined natural and forced convection phenomena. Interest also continues in transient effects and in convection with non-Newtonian fluids. Interest seems to be growing in convection in porous media as well as in the possibility of using a number of modifications of numerical techniques, such as finite element methods, to study natural convection.

Almost as numerous as ever are studies related to natural convection heat transfer from a vertical flat plate. One study [61F] compares different analytical approximations to predict laminar convection along a plate whose wall surface temperature has a power law distribution. Tables of Nusselt numbers have been prepared for natural convection in fluids of different Prandtl number along a non-isothermal plate [69F]. The influence on heat transfer of induced flow near the leading edge of a plate has been studied [38F]. Higher order approximations to the flow over a surface with uniform heat flux indicate corrections may be necessary in the normal boundary layer solutions at moderate and low Raleigh numbers [59F]. Use of an integral technique [14F] indicates the relative importance of viscous dissipation on natural convection heat transfer. An approximate solution for the heat transfer to a stably-stratified fluid agrees well with earlier results [77F]. Measurements of the thermal boundary layer indicate that at high Prandtl number, an enclosure can significantly influence the temperature profile around a vertically-heated plate [16F]. Natural convection effects in the laminar region above a flame along a vertical surface have been investigated [3F]. Variable suction velocity along a porous vertical plate introduces three-dimensional natural convection effects [91F].

Several investigations considered transient effects when the surface temperature of a vertical surface is changed with time. Measurements in the flow near such a wall which is suddenly heated, indicate the time when the influence of the leading edge is first felt at any given height [58F]. A finite difference solution indicates several extremes can occur in the heat transfer coefficient before a steady state is reached [49F]. The influence of the leading edge of a plate within a uniform transverse magnetic field was analyzed to determine the time at which pure conduction no longer dominates the heat transfer [64F]. Other studies considered the influence of plate motion on heat transfer to a rarefied gas with the plate oscillating [92F] or impulsively started [93F]. The time to go through a transient process of natural convection heat transfer has been considered [72F].

Several studies considered turbulent natural convection along a vertical plate. Use of one turbulence model indicates that the Nusselt number would vary as the Rayleigh number is raised to the 0.367 power [57F]. Space-time correlation measurements of the temperature and velocity fluctuations have been made [17F] on a constant temperature plate up to Rayleigh numbers of $10^{10}$. An analysis [78F] on the turbulent heat transfer from a rough vertical plate predicts the Nusselt number is proportional to the Grashof number raised to the one-half power. An analysis indicates the turbulent convective heat transfer from a vertical plate to a power law fluid [89F]. The heat transfer and structure of the turbulent thermal plume along a vertical isothermal wall were measured to approximate the flow that would occur above a fire [55F].

Considerable interest is still directed toward problems of natural convection in horizontal layers, in which the lower boundary is maintained at a higher temperature than the upper boundary. An examination of the convection rolls in low Prandtl number fluids indicates an increase in the wavelength of these rolls with an increase in Rayleigh number [22F]. At low Rayleigh numbers, the velocity field has been mapped using a laser-Doppler anemometer [27F]. A post-stability analysis of the amplitude of the velocity fields in convective rolls agrees with measurements obtained with a laser-Doppler anemometer [28F]. The effects of spatially-periodic thermal boundary conditions are greatly amplified near the classical critical Rayleigh number [52F]. The influence of variable viscosity on the convective heat transport can be obtained by considering the ratio of the actual critical Rayleigh number to that for a constant viscosity fluid [12F]. The effect of cylindrical sidewalls on convection near the critical Rayleigh number has been predicted [15F]. Surface tension was found to enhance the heat transfer in a horizontal layer of small thickness [41F]. Application of a magnetic field amplifies low temperature thermal convection in oxygen gas [42F]. The influence of small but finite heat transfer at the side walls in such a layer tends to influence the transitions in the flow [24F]. The effect of a horizontal temperature gradient on the stability of a fluid heated from below has been investigated [101F]. An experiment demonstrated the importance of density inversion on the heat transfer and onset of the flow in a layer of water over a surface of ice [86F]. A linear stability analysis found the density anomaly in water at 4°C has a stabilizing effect on flow transition [62F]. Numerical solutions provide a picture of the steady flow of non-Newtonian fluid in thermal convection [73F].

Natural convection in a cavity with parabolic sidewalls has been studied with reference to applications in solar collectors [1F]. Models have been developed to explain heat transfer across a horizontal cavity with differentially-heated endwalls [9F]. In a related study, an integral analysis was used to predict the convection through a horizontal duct connecting two fluid reservoirs at different temperatures [8F].

Some studies consider the heat transfer in horizontal layers of fluids in which volumetric energy sources are present. Situations such as this might occur in fluid layers undergoing chemical or nuclear reactions and have been of some interest to those examining nuclear reactor safety problems. In one study [21F], a simple model has been postulated to obtain correlations for Nusselt number with uniform energy sources. Stable hexagons are found in such layers at Rayleigh numbers up to somewhat more than three-and-one-half times the critical value [96F]. An analysis of the hydrodynamic stability confirms the applicability of an approximate empirical relation for determining the instability limit [71F]. In a layer undergoing a phase change at the upper surface, increased melting was found to destabilize the layer [107F].

A number of papers report on studies of convection in vertical layers. Different types of laminar cellular flow and the transition to turbulence have been examined visually in a vertical layer with differentially-heated sidewalls [84F]. A numerical analysis of buoyancy effects in a vertically-heated tube agrees well with experimental results [37F]. With a restricted entry in an open vertical duct, it is possible to have no throughflow at moderate Rayleigh numbers [29F]. The instability of a vertical layer, with differentially-heated sidewalls, has been studied with stably-stratified fluid [11F] and unstably-stratified fluid [35F].

The temperature profile has been measured in a vertical layer of air with one heated and one cooled sidewall [109F]. Laser-Doppler measurements show the three-dimensional flow in a vertical cavity [65F]. Flow visualization was used to obtain a model for the flow of fluids of different Prandtl number in a differentially-heated vertical cavity with different aspect ratios [85F]. A finite difference solution predicts natural convection in a vertical square cavity [80F]. Finite element methods have also been used to study natural convection in a square enclosure with differentially-heated sidewalls [60F]. A slightly conducting sidewall has significant influence on transitions in a two-dimensional box [39F]. The importance of a density inversion in a vertical cavity has been demonstrated by heat transfer measurements and flow visualization [86F]. A finite-difference solution for the convection in a two-dimensional enclosure with heat sources and heat sinks over the region of the upper surface has been demonstrated [23F]. The oscillatory flow in the plume above a line source in a rectangular enclosure has been measured [47F].

Numerical analysis was used to predict the natural convection across a vertical layer confined between one flat wall and a parallel wavy wall [97F]. For inclined layers between a flat wall and a parallel corrugated wall, a larger heat flux is obtained than if both walls are flat [31F]. The natural convection flow in an insulated horizontal pipe has been studied when the ends of the pipe are at different temperatures [10F].

Measurements have been made on free convection from a downward-facing heated inclined flat plate to water over a range of conditions from laminar to turbulent flow [32F]. A horizontal corrugated plate was found to lose more heat by natural convection than a horizontal finned plate [4F]. An analysis describes the natural convection around a horizontal oscillating heated plate [99F]. A holographic system was used to observe periodic fluctuations in free convection mass transfer from a horizontal surface [5F].

A three-dimensional similarity solution simulates the effect of buoyancy and variable viscosity on the flow over a heated cone in water [102F]. Non-linear solutions were found for the buoyancy-induced flow adjacent to an inclined heated wall immersed in a stably-stratified fluid [50F]. The time-dependent convective flow in a stably-stratified fluid around an inclined wall has been predicted [18F].

Finite element methods are being used to predict convective heat transfer. In one study [33F], the free convection flow around a hexagonal cylinder has been calculated. In another work [98F], the importance of the proper choice of finite element has been demonstrated.

Many studies consider natural convection in a porous material. Similarity solutions for steady and unsteady natural convection from a flat plate adjacent to a fluid in a porous media are summarized [51F]. The onset of longitudinal vortices in a porous media due to natural convection effects when the medium is over a horizontal heated surface of non-uniform temperature has been studied [45F].

The frequency of oscillation in a porous medium heated from below was found to vary as the Rayleigh number raised to the three-halves power [44F]. The onset of natural convection in a cylinder of water-saturated porous medium when heated from below has been analyzed [111F]. Integral methods were used to predict the heat transfer in porous layers adjacent to vertical and horizontal plates [19F].

Other studies considered flow in porous media in enclosures. A simple model has been used [112F] to derive flow and temperature fields for three-dimensional natural convective motion in a confined porous medium. Instability can be strongly influenced by large variations in viscosity and thermal expansion coefficients due to large temperature differences in a porous medium [43F]. Convection in a long, shallow cavity containing a fluid in a porous medium has been studied when heating occurs from one side [100F]. Conditions for the presence of three-dimensional flow with natural convection in a porous medium have been examined [95F]. Natural convection in a horizontal porous medium subjected to different sidewall temperatures has been studied, including the effects of permeability of endwalls, Rayleigh number and aspect ratio [7F]. A perturbation analysis predicts the natural convection in a porous medium containing a concentrated heat source [6F]. The effect of a layer of liquid above a porous bed of inductively-heated particles on the stability and heat transfer in the porous layer has been examined [79F].

Partial spectral expansions were used to predict natural convection flow in the regions between concentric cylinders and between concentric spheres [88F]. An experiment showed eccentricity has little effect on the average heat transfer across an annulus between two cylinders [54F]. Transient natural convection in a horizontal pipe containing water includes the effect of maximum density [20F].

Analyses using a series solution [56F] and a nonsimilarity technique [68F] appear to agree well with the results from finite difference solutions for the heat transfer from horizontal cylinders. Experiments have been performed on heat transfer from horizontal cylinders of different cross sections [70F]. Experimental measurements on a suddenly-heated horizontal wire indicate the different stages of transient flow at relatively low Rayleigh number [74F]. An approximate integral method predicts the convection of a visco-elastic fluid on a curved surface [90F]. Three-dimensional equations are reduced to a two-dimensional form for heat transfer from an isothermal infinite inclined circular cylinder [76F].

The conditions for inertial damping and resonance of cellular convection in a rotating fluid annulus have been demonstrated [25F]. Experiments on centrifugally-driven thermal convection in a rotating cylinder have been performed with moderate and high Prandtl number fluids [46F].

Several studies have been performed on free convection plumes and buoyant jets. The development of the plume above a vertical heated plate has been studied under laminar flow conditions [94F]. The heat transfer from a ridge in the form of an inverted "v" has been studied experimentally, including the separation and flow in the resulting plume [64F]. The dilution of buoyant jets entering a stagnant fluid has been measured [26F]. The influence of a transverse magnetic field on a laminar plume above a line heat source has been reported [36F]. Interferometric techniques for studying temperature fields in axisymmetric buoyant plumes have been described [13F]. The effect of buoyancy on laminar axisymmetric jets has been studied experimentally and analytically [53F]. Integral equations have been used to study the motion of a buoyant jet in a crossflow [82F].

Mixed convection, in which both a forced flow and buoyancy-induced flow are present, is the subject of several investigations. The relative strength of these forced and buoyancy-induced flows can vary, and this is usually an important parameter in determining the form of the heat transport variation.

Papers that consider mixed convection in boundary layer flows include one using a series truncation to obtain the solutions for both aiding and opposing flows on a semi-infinite vertical flat plate [2F]. The instability of a mixed convection along a vertical flat plate has been analyzed [66F]. Experiments on flow over a heated horizontal plate indicated that longitudinal vortices that are formed are the first stage in laminar-to-turbulent boundary layer transition [34F]. The ratio of the Grashof number divided by the Reynolds number raised to the three-halves power was found to correlate heat transfer for laminar forced flow over a heated horizontal plate [48F]. With forced flow along a horizontal cylinder, free convection effects become dominant some distance downstream from the leading edge [108F]. For such a flow, a variable viscosity can enhance the heat transfer and stabilize the boundary layer [106F]. The local Nusselt number and friction factor was found for aiding and opposing flow over a range of conditions from pure natural to pure forced convection for a flow over a sphere with uniform surface heat flux [67F]. A semi-empirical equation for mixed convection was obtained using values of Nusselt number for pure forced and pure free convection [81F]. Experiments with gas flowing down a heated vertical pipe at low turbulent Reynolds number indicated a reduction of friction factor and an increase in heat transfer due to buoyancy as compared to constant property conditions [30F]. Buoyancy effects on the velocity development of a magnetohydrodynamic flow in a vertical channel have been studied [110F].

Combined natural and forced convection in the entry region of a heated straight tube have been studied [103F]. In a related study, an analytical approximation was used to show different regimes of flow in the entry region [104F]. Simplified expressions have been obtained for the Nusselt number for laminar mixed convection in horizontal tubes [40F]. Mixed convection has also been studied in a heated curved pipe [105F].

Experiments with a horizontal tube heated only over 180 degrees of the circumference showed that buoyancy has a significant effect on Nusselt number at low Reynolds number if heated from the bottom, but little effect if the heated position is on top [83F]. Numerical techniques are used to analyze the laminar flow in a tube over a portion of its circumference [75F].

### CONVECTION FROM ROTATING SURFACES

The equation

$$Sh\,Sc^{-1}(0.5657 + Sc^{2/3}) = 0.620\,Re^{1/2}$$

was found [7G] by experiments to describe mass transfer from spinning disks up to a critical Reynolds number $Re_{\text{crit}} = 2.6 \times 10^5$. Experiments [6G] on the transfer mechanism from a rotating disk to non-Newtonian fluids established that the mass and heat transfer boundary layer thicknesses are always less than the hydrodynamic boundary layer thicknesses.

Equations were derived from an experimental study [4G] of heat transfer from an inward flow of air to coaxial disks rotating in the same direction and with the same angular velocity. The equations hold for turbulent and transitional flow. Asymptotic solutions were obtained [11G] describing convective heat transfer and frictional heating of a cone resting with its apex on a flat plate and rotating around an axis normal to the plate. The solution is for small Reynolds number and small cone angles. It includes variable properties.

Spatial oscillations and convection celles appear in the flow of a fluid enclosed in an annulus with end walls when the upper wall is insulated, whereas the lower wall displays a temperature gradient in radial direction [2G]. This occurs when critical values of the Ekman number are exceeded.

Pulsating temperatures and heat fluxes were calculated [12G] for turbulent non-isothermal flows in a rotating cylindrical pipe. Buoyancy induced laminar flow in a rotating spherical annulus was investigated [10G] for the condition that the inner surface or the outer surface rotates or where both move in opposite directions. Experiments [8G] determined heat transfer from the outer cylinder to a liquid flowing through an annulus for the condition that the inner cylinder rotates.

A numerical analysis [13G] established the temperature distribution in a rotating cylindrical body with a line heat source located at the surface with its axis parallel to the cylinder axis and with cooling provided along a line diametrically opposed. Exact solutions are presented [3G] for the equation of the thermal boundary layer for axisymmetric rotating bodies with arbitrary surface temperature distribution and self-similar velocity distribution. Momentum and heat transfer for forced flow moving with a laminar boundary layer over a rotating body can be expressed as a set of coupled ordinary differential equations by appropriate coordinate transformations [5G].

Very high heat transfer coefficients were found [1G] in experiments on the vaporization of water films in rotating radial pipes at centrifugal accelerations $10^3$–$10^4$ times the gravitational acceleration. Wetting and burnout were also studied. A solution [9G] of the laminar compressible boundary layer equations describing swirling flow through a nozzle established a strong effect of rotation on axial skin friction, whereas the effect on heat transfer is small.

## COMBINED HEAT AND MASS TRANSFER

A review [4H] of heat and mass transfer for laminar and turbulent flow over plates, cylinders and spheres was published. Extensive experiments [15H] studied heat transfer in a turbulent boundary layer on a rough surface with air injection through a porous plate. Sand grain roughness was simulated by spheres with 1.25 mm diameter. A correlating equation for smooth walls could be adapted to describe heat transfer on the rough wall for transitional and fully rough condition. Experimental results and a semi-empirical analysis [21H] describe heat and mass transfer on a permeable surface in the zone of transition from laminar to turbulent flow. Optimization procedures [8H] make it possible to minimize the coolant flow requirements by optimizing the distribution of injection holes over the film cooled surface. Superposition methods were used to describe the heat transfer effectiveness of the holes.

It was demonstrated by experiments [2H] that the film cooling effectiveness decreased with an increase of the turbulence intensity of the cooling air ejected through a slot of the film cooled wall into a hot gas stream. The effect of swirl of the main air flow over a rotating cylinder on the effectiveness of film cooling with slot injection was measured [16H] for swirl angles between 0 and 75° and for blowing rates from 0.45 to 1.4.

The ejection of a turbulent jet into a crossflow was treated by a three-dimensional numerical analysis [1H]. Anisotropic transport coefficients had to be introduced to obtain agreement for a blowing rate smaller than 0.1 at 90° injection and for a blowing rate smaller than 0.5 at 30° injection. No agreement was obtained beyond these values. Film cooling with ejection through two rows of holes is shown [10H] to be considerably more effective than ejection through one row. The heat transfer coefficients were found to be very close to those without ejection for blowing rates smaller than 1 when defined with the adiabatic wall temperature. Effects of positive and negative pressure gradients on the efficiency of film cooling were studied [3H] on a stationary gas turbine blade with ejection close to its nose.

Local and average heat transfer from arrays of impinging jets to a surface were measured [9H] for a square array of holes 10–15 diameters apart.

A simple analytical approximation [6H] describing laminar binary boundary-layer flow along a vaporizing layer agrees with numerical calculations and experiments on benzene evaporation. A Reynolds number based on the number of roughness elements per unit area is shown [12H] to dominate the boundary layer behavior for laminar boundary layer flow over a rough subliming surface. Carbon vaporization into a nonequilibrium stagnation-point boundary layer was analyzed [19H] for hydrogen and helium in the mainstream assuming frozen flow of the carbon species. The analysis simulates conditions for a Jupiter entry probe. A computer analysis of heat, mass, and momentum transfer for sheer flow over a wavy boundary layer can be applied to the flow of air over water [14H]. It includes the possibility of circulating eddies. Integral methods [20H] were used to analyze heat transfer on a spray-cooled cylinder by a water mist approaching normal to the cylinder axis and creating a liquid film on the cylinder surface. Numerical and asymptotic solutions [5H] describe laminar condensation heat, and mass transfer in the vicinity of the forward stagnation point of a spherical droplet. Transfer between steam, air, and absorbing fission products was considered. The Stefan problem describing freezing, melting, or drying on a plate or cylinder was extended [18H]. An analytic solution [7H] was obtained for a certain class of multicomponent mass transport situations with heterogeneous surface reactions using Lévêques approximation.

The non-linear problem of heat and mass transfer in capillary porous bodies was analyzed [17H] postulating that the phase transition does not occur in a sharp plane but in a zone of finite thickness. A method is presented [13H] for the calculation of transient heat and mass transfer in colloidal capillary porous bodies with internal heat sources. Tapered cylinders were used [11H] as models of a pore space to investigate heat and mass transfer in capillary systems.

## CHANGE OF PHASE

### *Boiling*

The nature of the emulsifying agent strongly affects pool boiling heat transfer in oil-in-water emulsions [49J]. Internal microconvection is the important mechanism for the enhanced heat transfer observed in highly subcooled liquids [56J]. Ünal [83J] determined the void fraction, incipient point of boiling, and the initial point of net vapor generation in sodium-heated, helically-coiled steam generator tubes. In [66J] the Alad'ev correlation for wall superheat is modified using a combination of surface and fluid properties. The unsteady-quenching method for determining boiling curves is evaluated [55J]. Sharma and Varshney [67J] discuss the Mikic–Rohsenow pool boiling correlation for pressures less than atmospheric. The correlation of Happel and Stephan correctly predicts nucleate boiling of liquified gases and their binary mixtures [85J]. The orientation of the heater surface is of major importance in nucleate boiling [12J]. There are contradictory views as to the effects of the thickness of the heater wall on boiling curves. Chuck and Meyers [17J] explain that previously observed effects were at opposite ends of the $\Delta T$ scale. The concept of bubble flux density, which is a function of both the active site density and the frequency of bubble departure, is used to correlate surface effects on nucleate boiling [48J, 68J]. Microlayer evaporation phenomenon is a significant heat transfer mechanism, especially at low pressures, since up to 40 per cent of the total heat transport is accounted for by microlayer evaporation [25J]. The size distribution of naturally occurring nucleation sites on a heater surface is determined [20J] by gas bubble nucleation and vapor bubble nucleation. More sites were active in gas diffusion than in boiling. In [76J] solutions for bubble growth rates including the effects of inertia, heat transfer, and microlayer evaporation were obtained in generalized coordinates. Formation and stability of a liquid microlayer is described by a balance of surface tension and deceleration force—in contrast to the usual boundary layer treatment [97J]. A model [4J], based on microlayer evaporation and drying-out phenomena, is proposed for interpretation of the deposition rate of suspended iron oxide on walls. The growth, departure, and implosion of small and large bubbles were analyzed [47J] utilizing semi-differential forms for the heat and mass equations. Bubbles grow more slowly in power law liquids the smaller the characteristic exponent [89J]. The size and shape of a bubble formed slowly on a sharp or round-edged orifice were derived with the help of a new analytical solution for the bubble profile [15J]. A closed-form, unsteady heat conduction solution, obtained by a double transformation, was used [73J] to estimate the evaporation rate at the perimeter of a growing bubble. The growth of vapor bubbles was studied in superheated liquids [58J], in combined gravitational and nonuniform temperature fields [34J], and for effects of internal circulation velocities and noncondensable gases [54J].

When a binary surface tension positive system boils, a maximum nucleate boiling heat flux is exhibited at a low concentration of the more volatile component [57J]. A DNB rivulet model was constructed [16J] to describe DNB temperature oscillation phenomena. Grigor'ev [28J] gives a theory of critical heat flux. In [37J] the available works on prediction of pool boiling stability that deal with infinitesimal temperature excursions on isothermal surfaces are extended to deal with nonisothermal surfaces and finite temperature deviations. Reference [21J] introduces a method by which the length of the annular flow regime in a straight vertical tube steam generator can be predicted and, therefore, the dry-out position located. The critical heat flux obtained with sudden increases in heater power depends on the initial condition in the wall layer produced by the initial power level [78J, 79J]. Heat transfer enhancement devices such as vanes, twisted tapes, or annular projections increase the critical heat flux up to 60% [62J]. Boiling crisis was studied [77J] in concentric and eccentric annuli with turbulence promoters on the unheated surface. Two papers [51J, 52J] report on boiling crisis in annuli with different axial heat flux distributions. Comparisons of calculated and experimental results are given for dryout in rod bundles [91J] and in vertical rod assemblies [2J]. A number of papers deal with the deterioration of heat transfer in the post dry-out region [41J, 75J, 86J]. An experimental study of surface rewetting of a copper tube by a falling film indicated the variations of surface heat flux behind the wet front to be similar to those observed in nucleate and film pool boiling [18J]. The Leidenfrost points for freon C51-12, 13, carbon tetrachloride, and chloroform were determined [22J] for pressures up to the critical pressure. A variable property analysis is available [42J] for laminar film boiling on vertical plates. Film boiling from the upper or lower sides of a horizontal plate was studied experimentally [64J].

A high thermal capacity test section was used to obtain flow boiling curves [13J]. Most existing correlations overpredict the heat transfer rates. The flow direction, i.e. the buoyancy forces, proved to have no effect on the critical heat flux [44J]. In [48J] surface tension is shown to play an important role for the onset of burnout phenomena, not only in ordinary pool boiling, but also in boiling systems with forced flow. Accurate analyses of the thermal behavior of a hot surface during rewetting (e.g. a nuclear fuel bundle during emergency core cooling) require reliable transition boiling data [14J]. A high thermal inertia hot patch was used for measuring film boiling at low qualities [29J]. An analysis is given for pressure excursions in transient film boiling [11J].

A number of papers examine the mechanics of evaporation of liquid droplets [95J] with heated surface whose temperature is below the maximum boiling rate point [93J]. In [43J] the entire boiling curve for a single droplet on a heated plate was measured and evaluated. In [65J] experiments also probed the transient temperature profile of a hot wall struck by an impinging liquid drop. Knowledge of the temperature field inside a vaporizing droplet is applied to a spray drying problem [94J]. Surfactants are a powerful tool to control evaporation processes [33J]. Features of boiling heat transfer in thermosyphons are determined that are different from pool boiling [6J, 7J]. Other papers deal with boiling with capillary porous structures [3J, 69J, 70J].

Two of the most important unknowns for the designers of boiling heat transfer equipment; the effect of multicomponent mixtures and multitube bundle geometry, were studied experimentally [38J, 87J].

### *Condensation*

Two fundamental papers on kinetic theory of evaporation and condensation describe linear and nonlinear problems [71J] and the hydrodynamic equation and slip boundary conditions [72J]. Results of linear stability analysis [84J] of film condensation indicate that surface tension, viscosity, and the overall effect of condensation mass transfer tend to stabilize while gravity tends to destabilize the flow. Reference [90J] summarizes five negative effects that a non-condensable gas exerts on condensation heat transfer [9J]. Heat transfer coefficients were determined for turbulent film condensation in a vertical channel [36J] using Deissler's expression for the eddy diffusivity [59J]. Finally, the effects on film condensation of surface force enhancement [60J], where the dynamic effect of the condensable on the condensate film is significant [5J], and of a chemically reacting gas ($N_2O_4 \rightleftarrows 2NO_2 \rightleftarrows 2NO + O_2$) [45J] are available.

Experimental data [50J] for dropwise condensation of steam on well prepared and characterized surfaces show that the heat transfer strongly depends on the hysteresis of the contact angle. Rose [61J] proposes that the extremely high rate of coalescence during dropwise condensation leads to space-and-timewise temperature fluctuations of such high frequency that the surface temperature is essentially steady—so that the material of the condensing surface plays a negligible role in determining vapor-side heat transfer. Hannemann [30J] gives an approximate analysis for the effect of condensing surface thickness on the constriction resistance and examines various dropwise thermal resistances as to their importance in design. Best rates of condensation heat transfer are obtained with polar fluids [8J]. Vibration affects the flow and heat transfer in film condensation [10J]. Condensation of wet steam on a widely spaced, staggered tube bundle placed in a foam bed [35J] is described. A surface renewal model has been developed for condensation inside a circular tube with in-line static mixers [23J]. Additional condensation papers from the Soviet Union are found in references [46J, 80J, 81J, 98J].

### *Two-phase flow*

The only liquid metal paper of the year [92J] concerns magnetic field effects on bubble growth in boiling liquid metals. Two-phase flows in capillary-porous bodies is the subject of five papers [27J, 39J, 40J, 82J, 96J]. The interactions that occur between a water downflow and a gas upflow on the rate of wetting of a hot vertical surface are described [19J]. Reference [53J] suggests using spectral noise analysis for determining the heat transfer mode in high rate boiling and for diagnosing the thermal state of the equipment. Intermittency functions have been defined [1J] which describe liquid, vapor, and interface regions at a fixed point in order to investigate statistical properties of temperature fluctuations in a boiling boundary layer. Two papers are given [24J, 74J] on melting thermodynamics. Two papers [31J, 32J] on bubble nucleation and growth in variable pressure fields deal with pressure oscillations. A new model [88J] for flashing of choked flow is more consistent in its assumptions than earlier models and predicts observed critical flow rates competitively. From measurements on a chilled tube [63J] the frost thickness turns out to be independent of the variables commonly significant in mass transfer such as Reynolds number and vapor pressure difference. A water pipe with no main flow in it may undergo 4–7°C of supercooling before ice nucleation occurs [26J].

## RADIATION

### *Radiation in participating media*

Radiative transport in emitting, absorbing and scattering non-gray media seems to attract increasing attention. The radiative flux and its divergence was formulated in terms of the total band absorptance for multidimensional problems involving non-gray radiating gases. Thus the frequency integration is eliminated, and the expressions are more compact [37K]. Approximate solutions obtained for radiative transfer in scattering absorbing plane-parallel media are compared with exact numerical solutions for both the isotropic and anisotropic cases. They agree within 10–25% which is adequate for most engineering applications [4K]. Approximate closed-form solutions are presented for the effects of optical thickness, anisotropic scattering, incident angle, polar angle and azimuthal angle for collimated radiation in a planar, conservative anisotropic scattering medium. Comparisons with exact solutions indicate that these dependencies are accurately predicted [2K]. A new method for calculating the spectrally integrated emission characteristics provides high accuracy without requiring excessive computer time [29K].

A two-dimensional model is used to predict the behavior of a semi-infinite isotropically scattering cylindrical medium exposed to collimated radiation. Comparisons with experimental results using a He–Ne laser beam incident normal to the surface of distilled water which contains latex paint as scattering centers show good agreement with the predictions of the model [18K]. A 2-D numerical algorithm is formulated for calculating radiative transfer in two dimensions through fog. The computer code generated from this algorithm is used to examine multiple scattering effects at wavelengths of 1.06, 3 and 10.6 $\mu$m [8K]. A solution is given to the radiative transfer of the solar irradiation through a turbid atmosphere bounded by a Lambert surface based on the single-scattering approximation [24K]. A comparison of predictions with measurements for radiative transfer in an algal suspension (scattering–absorbing medium) shows good agreement for the radiative fluxes if predictions are employed based on a six-flux model and the method of discrete ordinates [6K].

Spectral water vapor transmission data of the bands between 0.7 and 1 $\mu$m differ appreciably from values published by Moskalenko, which are the only spectral water vapor data below 1 $\mu$m applicable to real atmospheres [13K]. Measurements of water vapor continuum absorption in the 3.5–4.0 $\mu$m region show agreement with previous measurements by others for 65°C but the 23°C results indicate a continuum absorption which is larger than expected by about a factor of 2 [40K].

Solutions to the system of combined conduction and radiation for both non-gray and gray media having either conductive or convective boundary conditions at the top interface show that effects of top interface reflectance and internal scattering dominates the heat transfer behavior [27K]. By an analysis of combined conduction–radiation heat transfer through an irradiated semi-transparent plate the validity was checked of neglecting the interaction of conduction with radiation in the solid [38K]. Analytical and experimental studies of combined transient conduction–radiation heat transfer in selectively absorbing media are in satisfactory agreement [3K].

Combined radiative–convective–conductive heat transfer in the boundary layer of a combustion gas was analyzed by considering two infinite plates one of them exposed to a flow of hot gases. The results show that heat transfer to the wall will be increased if the latter plate exceeds the ignition temperature of the combustible gas and the combustion in the flow remains incomplete [31K]. The method of effective heat fluxes was used for investigating combined convection–radiation heat transfer in a closed system of gray bodies with a two-layer model of the gas medium [32K]. In a study of combined radiative–convective–conductive heat transfer in a dust-laden gas flowing in a flat duct, the effects are evaluated of particle size and density and of the scattering function on heat transfer [14K]. Measured temperature profiles for laminar convection in a $CO_2$ forced upflow are in good agreement with a simplified analysis which includes the effects of buoyancy and thermal radiation [9K].

The spectral and total emissivities of diatomic gases were calculated in the rigid rotor approximations using the Elsasser model of absorption bands. Results for CO, NO and OH are in satisfactory agreement with experimental data [25K]. For a treatment of vibrational nonequilibrium radiation of diatomic gases the authors derive in the first paper [15K] the macroscopic equations which describe the radiation field and the internal state of the gas. In the second paper [16K] they introduce approximations to the master equation for vibrational energy distributions of a diatomic gas. The calculated diffusion coefficient which is related to the mean absorption coefficient differs substantially from Planck and Rosseland values. Calculated infrared band absorption for nonrigid rotation (applied to CO, NO, $N_2O$ and $CO_2$) compares favorably with experimental data for small and moderate optical depths, but substantial differences exist for very large optical depths [5K]. Direct line-by-line integration and quasi-random band model techniques are used to calculate the spectral transmittance and total band absorptance of the 4.7 $\mu$m CO, 4.3 $\mu$m $CO_2$, 15 $\mu$m $CO_2$ and 5.35 $\mu$m NO bands. In almost all cases, the line-by-line results are in excellent agreement with experimental values [36K].

There is a close agreement between the various calculated mean absorption coefficients for luminous flames and for smoke which demonstrates the usefulness of the mean absorption coefficient concept for applications [11K]. Comparisons of calculated and measured radiative heat fluxes to the floor in a full-scale room fire show reasonable agreement [23K]. Measurements of the radiation in a methanol furnace showed that the radiative emission character of such a furnace is not significantly different from a furnace using other clean burning fuels, such as coke-oven gas and city gas [10K]. Results of absorbtivity measurements of enclosed industrial flames of gasoline, kerosene, diesel fuel, and oil in the visible and near infrared show that they are wavelength independent. The total absorptivities of these flames depend only on the excess air ratio [33K]. Investigations of radiative heat transfer in a layer of a gray gas impinging onto a heated surface may be of interest for the application of flat-flame burners [20K].

In the temperature range from $-3$ to $+80$°C the refractive index of water shows an exponential behavior as a function of the temperature [1K]. Studies of the effective infrared optical depths of the clear ocean indicate that this depth is better approximated by the reciprocal of the absorption coefficient as the wavelength increases [12K]. The use of mean (wavelength independent) radiation absorption properties may result in serious errors when predicting the absorption of solar radiation in water [39K]. Refractive indices of some common solvents are reported over their energy range of transparency from 2.1 eV (5,900 Å) in the visible up to 6.2 eV (2,000 Å) in the region of the UV absorption edge with an accuracy of $\pm 10^{-3}$ at room temperature [19K].

In a hypersonic flow of a radiating gas around the nose of a body which is subject to intensive evaporation, the flow region consists of the shock layer and a vapor layer in which radiation is partially absorbed. A similarity law is described for the radiative heat transfer coefficient at the stagnation point [22K]. On the basis of the mean properties of air at temperatures from $10^4$ to $2\times10^4$ K and pressures from 0.1 to 100 atm the radiative cooling of the air behind strong shock waves was calculated [41K]. Investigations of the shock wave structure of dusty gases which contain radiating particles show that ahead of the shock front, the particles are heated by radiative energy transfer from behind the shock front [21K]. Studies of how radiative heat transfer under optically thin conditions affects the process of sharpening or flattening of acceleration waves with planar, cylindrical and spherical symmetry demonstrate that radiative heat transfer delays the formation of a shock wave and has a stabilizing effect so that not all compressive acceleration waves will grow into shock waves [26K].

Thermal emissivity ($\varepsilon$) measurements of cholesteric liquid crystal films as a function of the film thickness ($d$) showed that $\varepsilon$ increases from 0.2 to 0.4 as $d$ increases from 13 to 33 $\mu$m and finally reaches a constant value as high as 0.87 for $d \approx 1$ mm [35K]. Considering photosensitized reactions in an absorbing–scattering medium within a plane slab it may be concluded that scattering will reduce conversion in all those situations where a good radial mixing occurs. Therefore conversion is more sensitive to the power absorbed within the slab per unit interspacial area than to the local rate of energy absorption [34K]. Studies of the effects of substrate reflectance and medium depth in a two-dimensional multiple scattering experiment reveal that the substance reflectance character and medium depth effects may be quite severe [17K].

A 300 W halogen lamp with a color temperature of 3200 K was utilized for studying radiative melting of a horizontal clear ice layer. Backmelting was clearly observed and predicted results of melting rates are in good agreement with measurements [28K]. Studies of the spectral reflectance of particulate materials using a Monte Carlo model including asperity scattering reveal that the theoretical values of reflectance, using the experimentally determined optical complex indices of refraction, compare well with the experimental reflectance observations [7K].

Modelling of heat and mass transfer in monolithic honeycomb catalysts, assuming an exothermic catalytic reaction occurring on a surface of a cylindrical passage, shows that radiation exchange can cause significant changes of the temperature distribution in the passage [30K].

*Surface radiation*

The total hemispherical emissivity of tungsten with an electropolished surface was measured [8L] for the first time at temperatures from 180 to 1000 K. The results depart significantly from theoretical predictions. Monochromatic bidirectional reflectance in the visible and near infrared range of water cryofilms on specular and diffuse surfaces of copper and epoxy were measured [5L]. Film thickness and incidence angles were varied and it was found that the reflected radiation retains the specular peak up to a film thickness of 500 $\mu$m. Generalized equations are presented [1L] for the calculation of absorptance, reflectance, and transmittance of any number of parallel surfaces. Radiation configuration factors are discussed for arrangements of disks [3L].

An analysis [4L] of solar and infrared radiation properties of parallel plate transparent honeycombs includes scattering and polarization. Calculations were performed for glass and mylar. A formula [9L] describes geometric factors for radiative exchange between plane specular v-shaped reflectors and collectors.

Scattering was analyzed [7L] for thin dielectric fibers with a diameter much smaller than the wave length. Planck's radiation law was generalized [2L] to anisotropic dispersive media.

The temperature of an injection-cooled and radiatively-heated perforated wall was analyzed [10L] considering air, argon, and helium as coolant. A numerical analysis [6L] describes radiative and convective heat transfer from a specularly reflecting surface with fins using the Monte Carlo method.

## MEASUREMENT TECHNIQUES

The development of measurement techniques and instrumentation related to heat-transfer studies continues to draw the interest of a number of investigators. Primary areas of activity included temperature and heat flux measurements, hot wire anemometry and transport property measurements. In addition, specialized techniques and equipment have been described for evaluating parameters such as heat and mass transfer coefficients and void fraction.

Calibration models have proven useful for describing and correcting measurements of the enthalpy of high temperature gas streams using gas-aspirated liquid-cooled calorimetric probes [29P]. Temperature measurements have been made inside a high-pressure vessel (pressures to 3000 bar) by enclosing a platinum resistance thermometer in a soft glass tube with sealed platinum contacts [45P]. The transfer function for a platinum wire used as a temperature sensor has been calculated in order to establish that the heat transfer between the sensor and its supports can appreciably effect the measurements [35P]. It was demonstrated that when a thermocouple is suitably interfaced with a microcomputer, a range of new possibilities arises for increasing the measurement accuracy of the thermocouple, particularly for such applications as high-frequency temperature measurements in turbulent combustion [48P].

A review of the phenomena and relationships encountered in surface temperature measurements is given which outlines methods of radiothermometry and proposes a number of methods of avoiding problems caused by unknown emission factors [17P]. The use of a high-sensitivity heat flux detector provides a contactless method of measuring the temperature of rotating metal surfaces at 313–353 K with an error not exceeding 1 K [22P]. The fabrication and principal characteristics of an electrically calibrated absolute radiometer are described and an instrument of this type is demonstrated to have an overall precision of at least 0.5% for the power level of 50 $\mu$W [8P]. Methods of obtaining quantitative thermometric data with a thermographic camera are presented, including a description of calibration techniques and an assessment of obtainable accuracies [11P].

The number of papers describing the evaluation, calibration and application of hot-wire anemometers continues to be large. A two-wire probe technique is proposed and analyzed for the simultaneous and continuous measurement of velocity and temperature in nonisothermal flows using a method that provides automatic compensation, even for large velocity and temperature fluctuations, over a frequency range of *d–c* to 6 kHz [26P]. Another technique for simultaneous measurement of velocity and temperature involves the conversion of analogue hot-wire anemometer voltage signals into digital forms which are processed on a digital computer in accordance with the anemometer response equations [30P]. When a hot-wire anemometer is calibrated at low velocities with flow in the horizontal direction, the heat transfer from the probe may be less than when the imposed velocity is zero [42P]. A relatively simple technique has been developed to evaluate the circulation associated with various spatial contours utilizing an X-geometry hot-wire probe [18P].

Errors occurring in hot-wire measurements in the vicinity of a wall and which are associated with the proximity of a heat-conducting surface in high velocity and temperature gradients were analyzed [40P]. The conduction between the sensor and the prongs can also lead to significant errors to measurements made in a turbulent flow near a wall [28P]. Application of a novel cross-correlation dynamic calibration technique has shown the significance of hot-wire end conduction losses for the measurement of stream temperature fluctuations under nonisothermal flow conditions and leads to recommendations of wire selection to minimize the effects of the losses [9P]. The X-geometry hot-wire probe with prongs perpendicular to the mean flow was found to be unacceptable for turbulence measurements [47P].

The number of reported investigations dealing with the theory and development of laser-Doppler anemometers has decreased significantly as the associated technology matures and the instrumentation becomes more prevalent in the laboratory. Recent observations demonstrate that CW laser-Doppler measurements can be made on smoke-stack plumes (and similar sources of pollution) at ranges approaching a kilometer. The good agreement between the laser measurements of both the exit speeds of the plume and the vortex shedding frequency of the stack and more conventional measurements of the quantities, provides confidence in the laser-Doppler data [10P]. At the other end of the spectrum, laser-Doppler measurements have been made in spatially restricted flow [14P]. A disadvantage of the laser-Doppler velocimeters which are currently on the market is their expense. One paper describes the construction of a comparatively inexpensive and simple velocimeter and presents experimental results to verify its effectiveness [41P].

The need to investigate the flow structure and turbulence beneath surface water waves led to the development and testing of a miniature drag sphere velocity probe [16P]. A pressure probe has been studied which can be rotated up to ±30° from the velocity vector with little error in the static pressure reading [27P]. Analytical and experimental studies of ASME flow nozzles were performed which resulted in new correlations for static pressure tap errors which, in turn, were applied to the theoretical nozzle discharge coefficients [6P].

Development continues in the area of transport property measurements. The steady-state method for determining the thermal conductivity of materials by measuring the one-dimensional heat transfer through cylindrical specimens has been improved by accounting for the thermal expansion of the specimen [34P]. A laser flash method which was previously developed for the measurement of thermal conductivity of solids has been successfully applied to liquids of low thermal conductivity (e.g. the thermal conductivities of water and toluene were measured by this method with a mean deviation of 2.6% [43P]).

Two papers address the measurement of thermal conductivity via the transient hot-wire technique. The first provides a contribution to the theory of the technique [31P] and the other describes its application to measuring the thermal conductivity of liquids [44P].

A transient method for measuring thermal properties of soils is superior to steady-state approaches in that it is faster, reduces the problem of moisture migration and simultaneously measures thermal conductivity and thermal diffusivity [2P]. An apparatus is described in which temperature and moisture content are simultaneously measured in a granular material through which one-dimensional heat transfer occurs, thus allowing the thermal conductivity to be established as a function of moisture content [25P]. A simulator for remote sensing and its application to solid moisture measurements are described [19P, 20P].

An instrument has been developed for the measurement of the product of density, specific heat and thermal conductivity of solid materials, a parameter which frequently occurs in analyses of unsteady heat conduction processes [1P]. The accuracy of a micro-transient thermal diffusivity measuring technique for liquids has been improved [23P]. The energy problem has been formulated and solved for biconical and concentric spherical viscometers [7P].

Instrumentation for the evaluation of radiation properties has been studied. A method is described for making *in situ* reflectance measurements of diffuse surfaces by using a GaAs laser and off-the-shelf optical components and the method does not involve the usual radiation integration over a hemisphere [12P]. A confocal mirror assembly was used to measure reflectances in excess of 0.99 with high precision [4P]. The measurement of radiation properties of selective surfaces using a solar calorimeter is described [46P]. The accuracy of portable instruments manufactured by Gier–Dunkle Instruments, Inc. and Willey Corporation for the measurement of solar absorptance and infrared emittance was evaluated in order to establish their applicability for testing solar selective surfaces [38P].

Two papers report measurements in two-phase flows. An optical probe, which has been miniaturized to reduce disturbances, can be used to evaluate local void fractions and interface velocities in liquid–vapor two-phase flows [3P]. A method of measuring the diameter of a transparent droplet in the absence of backlighting is described and its accuracy is experimentally investigated [13P].

Special instrumentation has been applied to measuring heat and mass transfer coefficients and shear stresses. The use of a differential interferometer with half-wavelength compensation has proven to be a good method for comparative investigations of convective heat transfer with such diverse fluids as nitrogen gas and silicone oil [36P]. The principal methods of measuring the convective transfer of momentum, heat and mass are surveyed on the basis of the three-fold analogy that exists between their transfer processes, and it is concluded that the simplest and most sensitive method is the mass transfer technique based on the principle of absorption with chemical reaction and coupled color reaction [32P]. Experiments of mass transfer in the presence of free and forced convection demonstrated that the camphene sublimation technique in connection with holographic interferometry is well suited for measuring local transport coefficients [24P]. As the result of new calibration techniques, the application of Preston tubes for the measurement of shear stress is extended to transpired turbulent boundary layers from near relaminarization to near blow-off conditions [15P].

English-language translations of Russian papers dealing with the following topics appeared in *Measurement Techniques*: (a) devices for the alignment [39P] and signal drift compensation [37P] of radiation pyrometers; (b) apparatus for measuring radiant flux density [21P, 33P]; and (c) resistance-thermometer errors caused by operating in still air [5P].

## HEAT TRANSFER APPLICATIONS

### *Heat exchangers and heat pipes*

The study of the performance of heat transfer surfaces for heat exchangers has found wide interest in recent years. The mass transfer analogy using naphthalene sublimation was used [8Q] to study heat transfer and pressure drop for a pair of colinear interrupted plates aligned with the flow. It was found that heat transfer increases with the thickness of the plates in the Reynolds number range which is usually used but that the pressure drop increases even more. A computer analysis [26Q] studied the details of laminar forced convection heat transfer from a shrouded longitudinal fin array with and without tip clearance. The presentation of heat exchanger performance by Kays and London was modified [25Q] to permit a ready comparison of plate fin surfaces. Experimental results [19Q] reveal the influence of various parameters on heat transfer in longitudinally finned tubes.

Local heat transfer rates at a tube in a bundle with crossflow were measured [20Q] at Reynolds numbers between $10^5$ and $10^6$. Drag coefficients for the first to fifth row are also reported. A numerical prediction [16Q] of the details of laminar flow and heat transfer in tube bundles used a cylindrical network close to the tubes and a Cartesian system for the rest. Agreement with experimental results by Bergelin was found satisfactory at Reynolds numbers between 1 and 1000. Heat transfer performance of tubes in longitudinal and crossflow was compared [12Q] based on the ratio of heat transferred to power required to drive the fluid. Naphthalene sublimation was used [27Q] to measure local heat transfer and pressure drop for a staggered wall attached array of cylinders with tip clearance to air flow in a rectangular channel. Developed conditions were attained after the fourth row. A method for calculating heat transfer [18Q] to staggered tube bundles in cross flow is described. Results of experiments [17Q] on the effect of thermal conductivity of fins arranged transversely on a tube in air flow are presented as a relation $Nu = C\,Re^m$ with $C$ and $m$ depending on the thermal conductivity of the fin metal. Heat transfer information is available for tubes with slotted transverse fins [13Q] and for shaped fins [1Q].

Several papers deal with the analysis of heat exchanger performance and with their dynamic characteristics. The deterioration in the thermal performance of cross flow heat exchangers due to the flow nonuniformity [4Q] and due to unequal temperature distribution [30Q] was analyzed. Longitudinal heat conduction in cross flow heat exchangers was found [5Q] to deteriorate the heat exchanger effectiveness. Design calculations of heat exchangers were developed [14Q] for heat exchangers with parallel-mixed flow including multi-shell heat exchangers. A number-of-entropy-production-units is proposed [2Q] as a general criterion for the rating of heat exchangers. Analyses consider the dynamic response of heat exchangers [28Q, 29Q] to step changes of velocity and temperature. Experimental results are compared [15Q] with standard predictions of the transient behavior of heat exchangers.

A few papers deal with regenerative heat exchangers. Charts are provided [11Q] from which the conditions can be determined for which heat conduction is important or can be neglected relative to convection. The transient behavior of regenerators can be studied in two papers [3Q, 22Q]. Improvements and new designs of Harrison plate fin regenerators for industrial gas turbines are discussed [7Q].

A one-dimensional model for the analysis of heat pipes [23Q] gives results in satisfactory agreement with experimental data, especially when the effects of suction and injection are included [24Q]. Experimental and analytical studies [10Q] on heat pipe performance were extended to supersonic velocities. Information is also presented [6Q] for heat pipes with a central tube artery. A small quantity of a noncondensable gas reduces heat transfer in a rotating heat pipe strongly [9Q] depending on the molecular weight of the noncondensing and working fluids. The response of a heat pipe to a step change in heat input was analyzed [21Q] using Fourier transformation.

### *Aircraft and space vehicles*

Over the past year there has been a substantial decline in publication activity in this field although space shuttle oriented work is still evident.

Analytical and experimental studies of roughness-induced boundary layer transition for the shuttle orbiter demonstrated that heat shield tile misalignment has only a slight effect on heat transfer and transition location for $T_w = 0.42T_t$. Cooling of the boundary layer causes the tile-induced disturbances to increase significantly, promoting premature transition [2R]. Flow visualization studies complemented by extensive heat transfer measurements at the leeside of an 80-degree swept delta wing at $M_\infty = 10$ revealed that the dominant contributor to the heating load are vortices generated by boundary layer separation, either at the leading edge or inboard [3R].

Taking the effect of temperature-dependent heat capacity on aerodynamic ablation of melting bodies into account, the surface temperature history and melting distance history have been calculated [5R]. An experimental study of transient ablation of Teflon showed that the heat flow inside the heat shield material parallel to the surface cannot be neglected which invalidates a one-dimensional analysis [1R].

Radiative heat transfer studies within a solid-propellant rocket motor indicate that most solid rocket exhaust flows are optically thick in the subsonic portion of the flow for all but the smallest motor, lowest chamber pressures, or lowest aluminum content propellants [4R].

### *General*

Experiments and numerical calculations considered processes in furnaces and steam boilers. A three-dimensional mathematical model [24S] used the Patankar–Spalding method to predict furnace heat transfer. The results describe the velocity and temperature pattern as well as the heat flux distribution in good agreement with experimental results obtained at the test facility of the International Flame Research Foundation in Holland. Heat transfer at various gas flow patterns in furnaces was simulated [12S] in channels. Experiments studied [28S] convective heat transfer in a vertical cyclone chamber. A model for transient heat flow to a liquid fuel droplet in combustion gas predicted [6S] the limit for micro-explosions. Local stability was examined [25S] by a nonlinear model of a fluidized bed steam generator. Measurements on 38 power plants [20S] revealed the effect of the thermal resistance of a slag layer on the efficiency of furnace water walls. Experimental results on temperature conditions in compact once-through steam generators are reported [26S].

A method for rapid numerical simulation of transient heat transfer to fuel pins of a nuclear reactor was developed [14S]. Laser holographic interferometry and analysis revealed the natural convection pattern in nuclear spent-fuel shipping casks [17S]. An analytic model describes [1S] surface heating by photon and ion irradiation in laser fusion reactors.

A new surface [7S] for cooling towers has water flowing down in grooves, whereas the rest of the surface is dry and acts like a fin. Experiments and analyses determined the performance of this heat transfer surface. Several papers [5S, 29S, 30S] deal with the performance of heat storage units.

A finite difference calculation [18S] and semi-empirical equations [3S] provide information on heat transfer in superconducting coils of electric machines. Flow and heat transfer in convectively cooled underground electric cables was determined experimentally [2S, 10S] and the results are presented by correlations of the form $Nu = f(Re\,Pr^{0.4})$ with the parameters based on the hydraulic diameter and including the effect of surface roughness. Laplace equations were used to analyze [21S] the effect of an elevated pipeline on moss covered ground on temperature. The temperature distribution in deep and shallow lakes was treated [9S] as a heat conduction problem with corrections for convection in some regions. Heat transfer for cased wells with perforations in shallow geothermal systems is described [15S] by a thermosyphon model. The correlation $St\,Pr^{2/3} = 0.0627 Syl^{-0.02} Re^{-0.498}$ with $Syl$ indicating the ratio of sensible to latent heat, describes the heat transfer characteristics of cooling and dehumidifying coils [22S] according to experimental results obtained in an air conditioning tunnel. New full scale tests [19S] provided data for heat transfer in insulated air duct systems.

Correlations for the Nusselt number in turbine cascades [32S] describe the effect of turbulence, rotation, and pressure gradient. Short duration measurements on gas turbine surfaces [11S] performed in a light-piston tunnel determined heat transfer to flat plates and curved surfaces simulating gas turbine surfaces. The effect of a concave curvature is found to be well described by Bradshaw's prediction. Transient heat transfer was measured [33S] on nozzle blades of an operating turbine. An analytic study [13S] considered heat transfer between a thin water film and the surface of a radial cooling channel of a gas turbine blade under the influence of centrifugal and Coriolis forces.

Several papers deal with heat transfer in the process industry. Calculation methods [16S] and optimization analysis [27S] considered heat transfer by convection and radiation in drying equipment and fermentation systems [8S]. The heat removal by cooling water in a mill used to reduce particle size in a slurry was studied [4S] with the aid of a mathematical model. Improved equations describing the relation between velocity and strain-rate fields in forging of rings were obtained [23S] by a numerical method. Wax or polyurethane liners of gun barrels reduce heat transfer caused by friction [31S]. In single firings the heat transfer is reduced by 10%. The reduction is even larger with multiple firings explaining a 25-times increase in wear life.

### *Solar energy*

The number of heat transfer related solar energy papers that appeared in the archival literature decreased. Two topics, collector performance and thermal energy storage, dominated the field.

The papers dealing with collector performance are divided nearly equally between the studies of flat plate and concentrating collectors. A definition of efficiency based on "convertable energy" or "potential work", which include the restrictions imposed by both the first and second laws of thermodynamics, has been proposed for solar collectors [12T]. The theory and the experimental procedure are described for simultaneously obtaining a number of points on the efficiency–temperature performance curve for a flat plate collector and a standard day is suggested to provide a basis of comparison between collectors [18T]. It was found that ambient temperature, flow rate and wind are the variables which most influence the performance of a water-trickle collector and the use of improved glazing material and double glazing are the design changes which significantly improve the collector's performance [2T]. Based on a model for the heat transfer in a flat plate collector with a rectangular flow passage, it was established that for a collector with circulation driven by natural convection the flow rate increases but the efficiency decreases when the flow passage is enlarged [5T]. Operational data is presented for a system using evacuated-tube solar collectors [10T].

An analytical study of a flat-sided rectilinear trough as a solar concentrator predicts that the practical concentration factor for such a device ranges from 1.5 to 4 [3T]. A similar study, by the same authors, investigated the concentrating properties of specularly reflecting pyramids, hexagons and circular cones [4T]. The radiative performance of a trapezoidal groove solar collector has been determined as a function of various directional distributions of insolation and the results are presented in the form of nomographs [1T]. An analysis of catenary shaped solar collectors indicates that moderate concentrations can be achieved over a range of incidence angles from 0 to 50° [17T]. The use of total internal reflection prismatic reflectors appears promising for a number of applications [15T]. An exact analytical method for determining the flux density of reflected sunlight from heliostats having polygonal boundaries has been developed [9T].

The performance of solar collectors can be enhanced by the use of selective solar absorber coatings to reduce the radiation heat losses, and by the use of transparent honeycomb materials to suppress natural convection. Solar selective surfaces consisting of a substrate of copper, silver, or nickel underlying a single thin layer of material were compared using the criterion of maximum net radiation transfer at a given surface temperature and copper was found to be the best substrate for a 200°C surface temperature [13T]. The residual absorption observed in sputtered amorphous silicon films makes them inefficient as selective absorbers for solar collectors [20T]. Globular all-metal films can have poor broadband selective properties; however, the addition of very thin dielectric layers between the globules and the substrate permits surface-wave resonances, giving broadband absorption and a higher solar selectivity [7T].

An approximate equation for predicting the solar transmittance of transparent honeycombs was found to be in reasonable agreement with measured results and should be very useful in the evaluation of systems, the interpretation of experimental results and the screening of candidate honeycomb materials [6T].

Both sensible and phase change approaches for storing thermal energy were investigated. A one-dimensional single-phase conductivity model of packed beds in which air and rock are at the same temperature was used to develop closed-form solutions for the transient responses produced by time-varying air inlet temperatures and these solutions were found to be in close agreement with long-term predictions based on more complex models [16T]. Heat losses from a packed bed thermal storage tank, due to imperfect insulation, dominate over internal thermal conduction effects in causing the degradation of the temperature stratification within the tank [11T]. An experimental study showed that, even at very large flow rates, thermal stratification can be maintained in cylindrical water tanks [8T]. A pressurized-liquid concept for solar-thermal energy storage is presented for continuous operation of power systems and it is predicted that the useful stored energy extraction efficiency would exceed 88% while operating in the neighborhood of 300°C [19T]. Storage systems using phase change materials require roughly one-half to one-fourth the storage volume of a rock bed unit or one-half to slightly more than the storage volume of a liquid-based unit [14T].

The use of passive solar heating and cooling systems also received attention. A general discussion of various types of passive solar heating and cooling systems is presented along with procedures for estimating the net daily energy gains for the systems [21T].

## PLASMA HEAT TRANSFER

Heat transfer studies in ionized gases continue to be of interest. Many papers are concerned with arc applications for circuit interruption. A numerical analysis of the Joule heating effect on plasma heat transfer to a positively biased body exposed to a plasma flow indicates that a certain fraction of the heat dissipated by the current flow in the vicinity of the body is transferred to the body [8U]. An analysis of the energy transfer to a negatively biased probe immersed into a plasma shows that at sufficiently high potentials the surrounding gas is heated and heat transfer to the probe surface is enhanced. Approximately half of the electrical power input is transferred to the probe surface [1U].

The behavior of high current density arcs ($> 10^3$ A/cm$^2$) burning in narrow channels of solid materials is governed by (1) arc induced evaporation of wall material, (2) axial convection and (3) radiation heat transfer [12U]. Studies of the arc behavior in narrow insulating channels showed that, in contrast to an open arc with convective cooling, the mean electrical conductivity of an arc burning in a narrow channel depends strongly on the currents [16U].

The reduction in radiation found in vertical mercury arcs at high pressures (up to 13 atm) is caused by self-absorption and not by increased radial heat losses because of turbulence or shear-induced eddies [19U]. Calculations of the radiative transport in wall-stabilized nitrogen arcs ($p = 1$ and 10 atm) showed that radiative losses account for a significant fraction of the power input. Losses for wavelengths $> 2000$ Å are most important for a wide range of conditions and the dominant contribution to these losses are due to line radiation [15U]. Measured values of electrical conductivity, emission coefficient for optically thin radiation, and thermal conductivity as a function of the temperature using a wall-stabilized arc in air at $p = 1$ atm compare favorably with theoretical predictions [5U].

Two forms of arcing damages are observed on carbon cathodes in atmospheric air: that due to the vapor (cold cathode) arc with current densities around $6 \times 10^7$ A/cm$^2$ and relatively low erosion rates, and that due to the thermionic arc (thermal arc mode) with current densities around $2 \times 10^3$ A/cm$^2$ and higher erosion rates caused by increased heating of the surface [9U]. For establishing a theory for the cathode mechanism in low-current vacuum arcs, the energy-balance equation, space charge equation, electron-emission equation, current equation, MHD equation of motion, and the minimum principle of Joule heating were taken into account. The calculated relationship between arc current and evaporation rate is in qualitative agreement with experimental data [10U]. A new non-stationary cathode spot model for metal vapor arcs differs from other known models by its emphasis on ion mass generation by Joule heating and the separation of energy flows associated with electron and ion currents in the cathode spot [4U]. Studies of the recovery of dielectric strength after current interruption in vacuum suggest that the effect of gross anode heating is important to the neutral decay because the highest temperatures reduce the tendency for vapor condensation at high currents where both anode and cathode surfaces become hot [6U].

Experimental results of gas blast arc studies near current zero show an enhanced electrical conductance decay at the orifice inlet. It is not yet clear whether this decay is due to radial heat conduction losses or whether additional processes need to be invoked [3U]. There is no need to incorporate radial turbulent cooling in the model description of an air blast arc circuit breaker in order to explain experimental results. If radial turbulent cooling is present, however, the interruption capability of the arc is substantially enhanced [17U]. Studies of power frequency scaling and of electrode vapor effects in gas blast arc circuit breakers showed that a small degree of vapor contamination (1%) by a low ionization potential material (Cu) can increase the electrical conductivity of the arc enough to halve its thermal recovery speed [7U].

Systematic measurements of the energy balance of thermal induction plasmas (argon) under different operating conditions using a 12 kW 500 Hz power supply clearly indicated that improvements of the coupling could increase the overall efficiency to more than 60%. Thus, the process-efficiency for plasma processing would be close to that of d.c. arcs [18U]. Calculations of the trajectories and temperature histories of alumina particles (10–250 $\mu$m) injected into the fire ball of an inductively coupled plasma indicate that internal plasma recirculation in the coil region is responsible for the observed rejection of the particles by the fire ball [2U].

Anode heat flux measurements in a quasisteady MPD plasma accelerator showed that for arc currents from 5.5 to 44 kA and argon mass flow rates from 1 to 48 g/s, the fraction of the total arc power transferred to the anode decreases from 50% at 200 kW to 10% at 20 MW [14U]. An analysis of electrothermal instability in the seeded combustion gas (MHD) boundary layer near cold electrodes demonstrates that the ratio of Joule heating to heat conduction by the gas governs the transition from a diffuse discharge mode to an arc mode triggered by small perturbation of gas temperature, electron temperature, current density and electron density [13U].

Investigations of the radiative transfer in pulsed laser plasma-target interactions indicate that the radiative contribution to the observed enhanced thermal coupling between plasma and target may be appreciable [11U].

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