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# HEAT TRANSFER—A REVIEW OF 1975 LITERATURE

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## INTRODUCTION

THIS review surveys results that have been published in various fields of heat transfer during 1975. 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 is available in the heat-transfer bibliographies published periodically in this journal.

The 15th National Heat Transfer Conference was held from 10 to 13 August, 1975 in San Francisco, California. Twenty-five sessions dealt with fundamental aspects of heat transfer and with applications such as nuclear technology and reactor safety, solar and geothermal energy systems, weather and climate, and fires. An invited lecture by C. F. Bonilla, the recipient of the 1974 Donald Q. Kern Award, discussed dewetting and rewetting. In another invited lecture, Peter Grassmann, recipient of the 1974 Max Jacob Memorial Award, reviewed heat transfer in the human body. A presentation of heat-transfer films and an open forum rounded out the program. The papers presented at the Conference are available as reprints and many of these will be published in the *Journal of Heat Transfer* or in the publication series of the American Institute of Chemical Engineers. Two heat-transfer courses within the *AIChE Today* series dealt with two-phase flow and fluidized bed heat transfer.

The 1975 International Seminar and Summer School was held during August at Dubrovnik, Yugoslavia organized by the International Centre for Heat and Mass Transfer. The focus of the seminar was "future energy production—heat and mass transfer problems". Nine sessions dealt with solar, nuclear, goethermal, and coal energy production and its impact on the environment. The Summer School provided an introduction to the same topics by means of invited lectures of experts in the field. A collection of papers of the conference will be available in book form from the Hemisphere Publishing Corporation.

The 96th Winter Annual Meeting of the American Society of Mechanical Engineers included in its program seventeen sessions on heat transfer. The trend towards greater concern with applications is evident in the topics of these sessions. Heat transfer in Arctic regions, geophysical energy, fuel rod design, gas turbines, heat exchangers for high temperature fluids, and discharge from power plants were discussed in addition to fundamental aspects. At the heat transfer dinner, ASME Heat Transfer Division memorial awards were presented to Simon Ostrach and to Peter Griffith. In the afternoon lecture, G. S. Lunney discussed the Apollo–Soyuz mission. Reprints of the papers are available from ASME Headquarters and many of them will also be published in the *Journal of Heat Transfer.*

The 1975 International Solar Energy Congress and Exposition was organized by the International Solar Energy Society from 28 July to 1 August at Los Angeles, California. Heat-transfer topics are found interwoven in many of the papers presented at the Conference.

A new journal, *Letters in Heat and Mass Transfer*, sponsored by the International Centre for Heat and Mass Transfer and published by Pergamon Press started publication late in 1974 and continued bimonthly during 1975. Its aim is to facilitate the exchange of information in the early stages of research via publication of short manuscripts that are published rapidly. It will, in this way, supplement the heat-transfer literature which is devoted to lengthier publications.

A number of books dealing with heat transfer or including heat-transfer topics have appeared on the market. They are listed at the end of the text portion of this review.

Precipitated by the energy crisis, there are strong indications that electricity will play a more important role in industrial processes in the future. Thermal plasma processing, which uses electricity as an energy source, is already attracting increasing interest as indicated by the following conferences in 1975: International Round Table on Study and Applications of Transport Phenomena in Thermal Plasmas, Workshop on Arc-Plasma Processing, 28th Annual Gaseous Electronics Conference, and the Symposium on Plasma Chemistry, Rome, Italy.

Developments in heat-transfer research during 1975 can be characterized by the following highlights: Heat conduction with phase change found attention in fourteen papers. Other topics in conduction included fins, contact resistance, thermal aspects of machining, and innovations and extensions of solution methods for transient problems. Laminar and turbulent channel flow heat transfer are treated in primarily analytical papers including entrance effects, curved ducts, and non-Newtonian fluids. Correlations for turbulent duct flow were reported. Papers on boundary layers treat unsteady laminar heat transfer and transition to turbulence. Analyses and experiments dealt with stagnation flow and crossflow on cylinders, as well as the effects of wall roughness. A significant review of heat transfer in separated regions on single bodies is worthy of mention. Separated regions in boiler tubes are being considered for particle collection. Numerical analyses of cavity flow and modelling studies for packed and fluidized systems are reported.

Detailed investigations of transfer mechanisms included measurements of instantaneous turbulent parameters, mathematical–statistical analyses of turbulence, and development of semi-empirical turbulence models. A review paper presents and compares more than thirty models for the turbulent Prandtl number. Remarkable activity is evidenced in the large number of analytical, numerical, and experimental papers on natural convection, occasionally applications oriented. Some of the papers include rotational effects. This may explain the small number of papers reviewed in the section on convection from rotating surfaces. Investigations on heat and mass transfer were mostly application dominated. Modern instrumentation facilitated detailed studies of processes with change of phase. Specific applications were considered, especially in the literature from the USSR. Surface rewetting also found considerable attention.

Analytical investigations dealt with radiative energy transport by emission, absorption, and scattering in gray and non-gray bodies. Radiation characteristics of cavities were analyzed. Liquid metal heat-transfer studies considered boiling and bubble formation. The laser–Doppler measurement method appears to be limited in its application by shortcomings existing in the processing techniques as evidenced by a number of papers devoted to this subject. The hot wire or hot film is still used for detailed flow studies. Temperature measurements in cryogenic fluids, and a new thermocouple which is corrosion resistant to 1300°C, were reported. Naphthalene is being used for the mass transfer analogy to heat transfer. Thermal transport properties were measured with new apparatus.

The literature contains an ever-increasing number of papers on specific applications. This applies to heat exchangers as well as to heat pipes and especially to solar heat transfer. Improved performance of flat plate collectors by selective coatings, by augmenting mirrors, and by vacuum insulation is discussed. Underground thermal energy storage and phase change storage material found attention. The number of papers dealing with aircraft applications has, on the other hand, declined. Those published consider mainly the heat shield and ablation for the space shuttle.

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

Conduction, A
Channel flow, B
Boundary-layer and external flows, C
Flow with separated regions, D
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
Liquid metals, M
Measurements 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

Topics of major interest among papers dealing with heat conduction included phase change, fins, heat-involved machining operations, contact resistance, and solution methods for transient problems.

The moving phase boundary can be eliminated from the analysis of conduction phase change problems by employing the enthalpy as a dependent variable along with the temperature. This formulation is applicable both to substances that have a discrete phase change temperature and to those that change phase over a range of temperatures. Its application to multidimensional phase change problems has been carried out with the aid of a fully implicit finite difference scheme [65A]. A related approach is to define an equivalent heat capacity such that the latent heat is included. One-dimensional solutions based on such a model gave results in satisfactory agreement with experiments on the freezing of water [35A]. Since the solid–liquid interface is a surface of constant temperature in a phase change problem, the use of the temperature as an independent variable affords certain simplifications [15A]. Another procedure for neutralizing the complications of the moving interface is to immobilize the interface by a coordinate transformation [16A]. Both methods were illustrated by application to two-dimensional phase change problems [15A, 16A]. A new perturbation method for one-dimensional phase change problems involves preparatory transformations which immobilize the interface and replace the time variable by the time-dependent interface position [28A, 29A]. Another proposed approach for solving one-dimensional phase change problems is to use finite differences for the time derivative and to work with differential equations in the space coordinate [20A].

In the self-freezing technique of freeze drying, there are two moving phase boundaries, one between the subliming solid and its vapor and the other between the freezing liquid and its solid [27A]. The transient melting of a vertically oriented solid which results from the condensation of a vapor gives rise to a liquid film to which both the melting solid and the condensing vapor contribute mass [14A]. A coupled heat- and mass-transfer problem which is related to drying of a porous medium is characterized by an evaporation front which moves according to a square root of time relationship; the problem yields a similarity solution [13A, 50A]. For glass-like materials which solidify over a range of temperatures, account was taken of the variation of viscosity which accompanies the transition from liquid to solid [30A]. Extensive freezing front results, based on numerical solutions, have been obtained for plane, cylindrical, and spherical geometries and for a variety of thermal boundary conditions [68A]. Solidification of a superheated liquid due to a constant surface heat flux was solved by a finite difference method [22A].

Fins (i.e. extended surfaces) continue to be an active applications area. There is a temperature depression at the base of a fin owing to the heat-transfer augmentation caused by the fin. The extent of the depression is affected by the proximity of adjacent fins [67A]. For a fin whose base is subjected to either a step change of temperature or of heat flux, the time to reach steady state is appreciably longer for the latter than for the former [69A]. For a timewise periodic variation of the base temperature, the temperature oscillations in an annular fin are smaller than those in a straight rectangular fin [2A]. By taking account of the curvature of the fin profile in the optimization procedure, the least-weight circular fin was found to be substantially shorter than that obtained by neglecting surface curvature [24A]. The use of a perturbation method enabled a closed-form solution for a rectangular fin with variable thermal conductivity and facilitated evaluation of optimum fin dimensions [3A]. A lamination made up of sheets of conducting paper pasted together has been proposed as an electrical analogue for determining the performance of two-dimensional fins [58A]. The effect of axial conduction in a thin plate adjacent to a laminar wedge-type boundary-layer flow can either decrease or increase the Nusselt number depending on the wedge-angle parameter [63A].

A number of papers were concerned with thermal aspects of machining and fabrication. The solution for the temperature field due to a moving diffuse heat source served as the basis for a relationship between power density and cut speed that is applicable to thermal cutting techniques (lasers, electron beams, plasma jets, etc.) [7A]. Electrical discharge machining can be modeled as a point surface heat source whose effects propagate into the material and cause melting and evaporation [73A]. The solution for heat conduction in a translationally and rotationally moving cylinder under the influence of a system of concentrated and distributed surface heat sources has application to the machining of a cylinder by a set of grinders or cutters [34A]. Temperatures in machining processes, as calculated by moving heat source theory, can be affected by variable properties and, in particular, the maximum surface temperature is found to be significantly higher for a variable property analysis than for a constant property analysis [31A]. In another paper involving motion of a heat source and motivated by machining and heat treatment applications, conditions are derived for delineating when energy transport due to conduction or convection in the direction of motion can be neglected [57A]. The relatively slow diffusion of heat, relative to the speed of a moving heat source, facilitated the analysis of the temperature distribution in a welding process [5A]. The finiteness or non-finiteness of the temperature of heat sources was examined for point and line sources, either instantaneous or continuous [36A].

Papers were also motivated by other applications. An analysis of the temperature field in the insulation of an electric power cable identified the penalties of circumferentially nonuniform cooling [9A]. Transient heat-conduction solutions enabled an evaluation of a rock crushing technique consisting of surface heating followed by cooling [12A]. The temperature response of a porous, transpiration-cooled matrix to a sudden initiation of internal heating is significantly affected by the transpiration flow rate [8A]. The implementation of a technique for determining the thermal conductivity of metals and semi-conductors has motivated analytical and numerical solutions for the temperature distribution in a thin wire with radiative heat loss [32A]. Experiments involving an array of copper rods in an electrolytic bath confirmed predictions of apparent thermal conductivity for a medium containing parallel fibrous elements [62A].

Various aspects of thermal contact have been studied. An explanation of observed directional thermal resistance at a contact between two materials is based on differing degrees of distortion of the contacting surfaces in response to thermal expansion [33A, 61A]. Experiments with air, argon, and helium as interfacial fluids in contact resistance studies showed that the resistance is especially affected by the presence of the fluids when the contact pressure is low [44A]. At atmospheric pressure, the resistance at a steel-to-steel contact was increased by insertion of a soft, high-conductivity metallic gauze, but a reduction occurred under high vacuum conditions [53A]. Temperature extrapolations have been shown to be the probable cause of discrepancies among various published results for thermal contact resistance [72A]. Constriction resistances associated with the flow of heat from a larger to a smaller cross section were determined for cylindrical shells with either axial or circumferential ribs [19A]. The bonding of a cylinder to a plane wall gives rise to a thermal resistance which can be evaluated from a simple algebraic expression [1A].

Innovations and extensions related to solution methods for transient problems have been described. In a collocation method for the solution of nonlinear transient one-dimensional heat conduction problems, the dependent variable is expanded in cubic splines in the space variable at each time step, and the unknown coefficients in the expansion are obtained by satisfying the governing differential equations at a finite number of points [10A]. In lieu of discretizing the time derivative in a finite difference or finite element scheme for the spatial variables, a procedure based on formally integrating the ordinary differential equation in time is proposed [54A]. The advantages and disadvantages of the least squares time-stepping algorithm for two-dimensional transient conduction problems have been aired with the aid of examples [6A]. Numerical examples were also employed to illustrate the characteristics of a solution procedure which uses finite element discretization for both space and time [38A]. The theory of complementary variational principles was used to obtain solutions for two nonlinear transient one-dimensional diffusion problems involving concentration-dependent diffusion coefficients [59A]. A variational method for obtaining approximate solutions for transient problems with variable thermal conductivity has been developed and illustrated by an example problem [40A]. A closed form solution for transient conduction in a slab with variable thermal conductivity was obtained on the basis of an assumed parabolic profile for the spatial distribution of the temperature [46A]. The importance of selecting a proper temperature representation for use with the Heat Balance Integral was underscored in a problem involving variable thermal conductivity and specific heat [26A].

The hyperbolic heat-conduction equation, which leads to a finite speed of propagation of temperature waves, can be derived by replacing Fourier's law with a more general constitutive relation [60A]. The ordinary heat equation and the hyperbolic heat equation give markedly different interface temperatures at the first instant of contact of two solids, but the deviations disappear rapidly [37A].

A layered anisotropic composite has been modeled as an anisotropic but homogeneous equivalent material, with an apparent conductivity tensor expressed in terms of the properties of the constituent layers [71A]. Solutions have been developed for the transient temperature field in laminated composite slabs and cylinders composed of any number of distinct lamina, each with its own fully populated conductivity tensor and heat source [55A].

For steady conduction, shape factors have been tabulated for about 50 geometrical configurations [25A]. The thermal resistance of a solid cylinder subjected to different temperatures on isolated portions of its circumference was determined by conformal mapping [64A]. A classical separation of variables solution for steady conduction in a finite circular cylinder was numerically evaluated to obtain temperature fields corresponding to prescribed polynomial temperature distributions on one of the end faces of the cylinder [45A].

Some papers dealt with more theoretical aspects. In a fundamental paper, heat-conduction processes are related to the principle of the least dissipation of energy [17A]. Finite integral transforms were used to schematically indicate the solution for the heat equation with time-dependent coefficients, but no applications are given [49A]. A variational principle was used to deduce error bounds for one-dimensional steady temperature solutions with variable thermal conductivity [18A]. In a highly mathematical treatment, solutions for the problem of heat and mass transfer in a sphere are presented in terms of lengthy formulas [70A].

English-language translations of Russian papers dealing with the following heat-conduction topics have appeared in *Heat Transfer/Soviet Research, Thermal Engineering*, and *Soviet Physics/Technical Physics*: (a) one-dimensional transient conduction in a multilayer medium [51A], in a slab with radiant heat loss [39A], and in a porous plate [52A]; (b) corrections of transient temperature measurements [43A]; (c) construction of Green's functions for one-dimensional transient conduction [76A]; (d) a variational method for two-dimensional transient conduction [75A]; (e) a method for solving multi-dimensional transients whereby a resistance network is employed to solve for the Laplace-transformed temperature function [66A]; (f) unsteady finite difference equations for conical and spherical bodies [21A]; (g) approximate transient temperature solutions for cylindrical regions used as input for thermal stress calculations [74A]; (h) transient temperature field in a cooled turbine blade [56A]; (i) conduction phase change with moving boundaries [11A, 23A]; (j) errors between one- and two-dimensional quasi-steady solutions for a two-layer disk [48A]; (k) steady-state temperature distributions in a disk with radiative heat loss [4A] and in a hollow heat-generating cylinder with internal convective cooling [41A]; (l) effect of nonuniform surface convection on the efficiency of a fin [42A]; (m) effect of longitudinal conduction on the temperature of a wall cooled by convection [47A].

## CHANNEL FLOW

Publications dealing with duct-flow heat transfer have tended to be predominately analytical, with a special interest in correlation of turbulent heat-transfer results.

A single equation which correlates variable-property turbulent heat-transfer data for liquids and gases involves the Nusselt, Reynolds, and Prandtl numbers, respectively evaluated with bulk, film, and wall properties [44B]. A correlation based on a Stanton number which contains the friction velocity purports to encompass all available turbulent pipe flow data, including data corresponding to moderate wall roughness [21B]. Hausen's [1959] correlation equation for the Nusselt number for turbulent pipe flow has been updated to account for discrepancies at higher Reynolds numbers and intermediate Prandtl numbers [19B]. An independent correlation effort, also prompted by the inadequacies of the Hausen equation, yielded still another Nusselt number representation for turbulent pipe flow [14B]. A friction factor correlation for noncircular ducts was extended to the turbulent flow Nusselt number by means of an analogy between momentum and heat transfer [31B].

Several topics were treated in analyses of turbulent flows. Additional differential equations for turbulent velocity correlations and scales formed the basis of an analysis of flow and heat transfer in an annulus [18B]. Separation of variables and an eddy-diffusivity-type turbulence model were employed to obtain entrance region and fully developed heat-transfer results for annuli over a range of Prandtl numbers from 0 to 100 and a range of Reynolds numbers from $10^4$ to $10^5$ [12B]. In a companion paper, provision was made for different eddy diffusivities in the radial and tangential directions to accommodate circumferentially varying thermal boundary conditions [11B]. The accounting of viscous dissipation for turbulent pipe flow of a liquid markedly influences the sensitivity of the Nusselt number to variations of the Reynolds number [40B]. A formal solution of the turbulent channel-flow energy equation for the spatial (or timewise) decay of an inlet (or an initial) temperature distribution was partially evaluated with the aid of experiments [26B]. The surface roughness configuration needed for the attainment of a high heat-transfer coefficient is different from that for the attainment of an optimum efficiency which takes account of both heat transfer and friction [29B]. Numerical solutions for turbulent pipe flow of water and carbon dioxide near the critical point agreed well with experimental data for cases where the wall temperature at the inlet is less than the pseudocritical temperature of the fluid [42B].

Some papers dealt with turbulent flow experiments. For supercritical helium with an inlet bulk temperature less than the transposed critical temperature and with high heat fluxes at the tube wall, the heat-transfer coefficient passes through a maximum and then deteriorates as the fluid temperature approaches the transposed critical temperature [13B]. The imparting of swirl at the inlet of a tube resulted in increases of up to a factor of eight in the heat-transfer coefficient for turbulent airflow [20B]. In another investigation with water as the working fluid and with a different swirl generation configuration, increases of up to 80% were reported [52B]. Evidence of laminarization of a low-Reynolds-number turbulent pipe flow by heating was provided by measured fluid temperature profiles [41B]. Nusselt numbers for longitudinal turbulent flow of water in closely spaced rod bundles are affected by the circumferential distribution of temperature in the bounding walls [4B].

Laminar entrance region problems continue to be of interest. For a concentric annulus with simultaneously developing laminar velocity and temperature fields, higher Nusselt numbers are attained when the inner wall is heated than when the outer wall is heated (with the alternate wall being adiabatic) [8B]. The gap between the Lévêque and Graetz solutions, which are respectively valid very near the inlet and farther downstream, has been bridged [37B]. The values of Graetz number for which thermally developed conditions prevail were established by examining the entrance region solution for slug flow in a parallel plate channel [15B]. The accounting of radiative transfer in a laminar pipe flow gives rise to an upstream propagation of energy from the heated surface of the pipe [10B]. Higher order polynomials used in conjunction with the integral momentum and energy equations yielded entrance region Nusselt numbers for the parallel plate channel that differ little from the already available results based on lower order polynomials [38B]. For slug flow in a tube with an external convective boundary condition, an approximate solution compares favorably with an already available exact solution [50B]. For pipe flow with a spatial step change in wall heat flux, orthogonality relations between the eigenfunctions have been established which simplify the solution [45B].

Heat transfer for laminar flow in curved ducts has been subjected to analysis. Numerical calculations for the Graetz problem in a curved duct of square cross section show that the length of the entrance region is diminished as a result of curvature [6B]. In the presence of duct curvature, variations of the Biot number associated with an external convective boundary condition have little influence on the Nusselt number [7B]. A series solution, using the ratio of the pipe radius to its radius of curvature as an expansion parameter, was employed for analyzing fully developed laminar flow and heat transfer in a curved pipe [51B]. The axial dispersion of a solute in a laminar pipe flow is markedly reduced when the pipe is coiled [48B].

Various other laminar heat-transfer problems were analyzed. The Weiner–Hopf method was employed to determine the relative heat-transfer rates from a pair of in-line plates situated in a laminar slug flow in a duct [27B]. In high shear stress capillary viscometry, convection is the primary mechanism in the removal of the dissipated heat [23B]. Fully developed laminar flows in rectangular ducts admit analytical solutions for a variety of temperature dependences of the viscosity and thermal conductivity [17B]. A least-squares technique of satisfying boundary conditions enabled the determination of fully developed friction factors and Nusselt numbers for laminar flow in a variety of non-circular ducts [43B]. A generalized analysis yielded the temperature fields in Couette flows encompassing many different gap configurations [3B]. Couette flow solutions corresponding to linear viscosity–temperature and conductivity–temperature variations were used as a basis for estimating variable property effects in laminar tube flows [5B].

Non-Newtonian effects nave been investigated. The Nusselt numbers for power-law pseudoplastic fluids in laminar pipe flow are higher than those for Newtonian fluids [30B]. Solutions for an Ellis-model non-Newtonian fluid in a parallel plate channel indicate that the thermal entrance length is greater than that for a Newtonian fluid [34B]. Little difference was found between the heat-transfer results respectively based on the power-law model and on the Ellis model for laminar non-Newtonian flow in a concentric annulus [46B]. Experiments on laminar pipe flow of a non-Newtonian fluid showed that the temperature-dependent viscous properties affected the local rate of heat transfer more than did the non-Newtonian characteristics [2B]. The transfer processes for turbulent pipe flow of a non-Newtonian power-law fluid in the presence of mass diffusion and chemical reaction were found to be highly sensitive to the reaction parameter and the reaction order [36B].

Some results for mass-transfer processes have been published. Solutions for trace diffusion of material from a tube wall into a laminar pulsatile flow gave time- and space-average interphase fluxes that are lower than the space-average flux for steady flow [33B]. Numerical solutions have demonstrated the non-validity of the widely accepted viewpoint that in a tube or channel through which a solute is diffusing, the solvent is stagnant [35B]. Local mass transfer rates determined from measurements of the dissolution of a benzoic acid surface enabled the evaluation of local Sherwood numbers for laminar flow in an annulus [49B]. Perturbation methods were used to solve for the axial dispersion of heat or mass in a tubular reactor under conditions where the reaction rate is nonlinear [32B].

A modest amount of activity continues for magnetohydrodynamic duct flows. The hall effect and ion slip have significant influence on the fully developed laminar heat-transfer conditions in an MHD channel [25B], as do pressure work and wall conductance [24B]. By the use of a Couette flow model of a slider bearing, it was concluded that the application of a magnetic field in addition to mass injection leads to significant reduction in the effects of heating associated with viscous dissipation [1B].

English-language translations of Russian papers dealing with the following duct-flow heat-transfer topics have been published in *Heat Transfer/Soviet Research* and in *Thermal Engineering*: (a) criteria for assessing heat-transfer augmentation [9B] and results of augmentation experiments [16B, 53B]; (b) experiments on high temperature and dissociating gas flows, respectively involving argon [47B] and nitrogen tetroxide [39B]; (c) correlation of rod-bundle turbulent heat-transfer data for air, water and steam [22B]; and (d) unsteady forced convection heat transfer in tubes [28B].

## BOUNDARY LAYER AND EXTERNAL FLOWS

Among the mathematical studies of boundary-layer problems, some analytical solutions of the Falkner–Skan equation have been obtained [49C] and some earlier solutions have been discussed [41C]. A mathematical formulation of the second-order thermal boundary-layer problem has been presented [32C]. Second-order solutions have been obtained for the flow past a blunt wedge by a power-series method [28C]. Merk's method for the calculation of heat transfer in a non-similar boundary layer has been extended to the case of a non-isothermal surface [33C]. Mathematical properties of a boundary-layer solution for the flow past a flat plate with a parabolic leading edge have been examined [47C]. A comparison of the accuracy of several finite-difference techniques for solving the boundary-layer equations has been made [5C]. A numerical solution has been developed for the calculation of boundary layers when the wall shear stress is specified [7C].

In laminar flow investigations, an analytical solution has been obtained for the heat transfer from a wedge with a step change in the wall temperature [11C]; also, some boundary-layer solutions have been worked out for the flow over a plate with arbitrary suction or injection [18C]. An exact solution has been obtained for the unsteady heat transfer between a fluid and a plate [39C]; and the problem of the unsteady thermal boundary layer on an impulsively started flat plate has been solved numerically [45C]. The combined radiation and convection heat transfer in reacting gas mixtures has been analyzed [36C]. Numerical solutions for laminar hypersonic flow in a dissociated boundary layer have been presented and the results of different simplifications have been examined [13C]. Analytical results for various non-Newtonian boundary layers have been obtained by the use of the local nonsimilarity method [15C]. Interferometric studies have been reported for the thermal boundary layer during the cooling of a vertical plate [17C]. A multi-component diffusion analysis has been made with constant properties (evaluated at a reference state) and shown to be quite accurate [40C].

Various aspects of turbulent boundary layers have been the subject of many studies. The behavior of a turbulent boundary layer on a concave wall has been studied experimentally [35C]. Numerical predictions have been reported for some three-dimensional boundary layers; the turbulent stresses have been modeled by an eddy–viscosity formulation [6C]. For supersonic turbulent boundary layers, the variation of the turbulent Prandtl number has been obtained from experimental measurements [25C]. A finite-difference solution of the compressible turbulent boundary layer on an infinite yawed airfoil has been reported [2C]. The surface renewal model has been applied to compressible turbulent flow [14C]. Heat transfer on a plate under high flow acceleration has been experimentally studied [27C]; an integral form of the turbulence kinetic-energy equation has been used in a turbulence model to predict the turbulent boundary layers in strong favorable pressure gradients [21C].

Transition from laminar to turbulent flow has been studied to some extent. Heat flux measurements have been obtained for a transition boundary layer on a plate [23C]. A theory based on the integral turbulence kinetic-energy equation has been applied to predict the transition from laminar to turbulent flow in a hypersonic boundary layer [34C]. A two-equation turbulence model has been used to predict the laminar-to-turbulent transition in a boundary layer down a vertical plate [29C].

The influence of wall roughness on the turbulent boundary layer has been investigated. Mean velocity and turbulence intensity measurements have been made for a fully-developed turbulent boundary layer over a square-groove type wall roughness [48C]; also, for the same type of roughness, measurements and calculations have been performed for a turbulent boundary layer with a step change in the wall roughness [3C]. The effect of heat addition and surface roughness on the urban boundary layer has been examined by a numerical method [16C]. An experimental study of the heat transfer between a twisted rod and a longitudinal flow has shown that there is no increase in heat transfer compared with an untwisted rod [43C].

A number of studies have been concerned with the flow over a cylinder. Experimental measurements have been reported for: the heat transfer from a smooth circular cylinder [1C], the effect of free-stream turbulence on the heat transfer from heated cylinders [24C], the heat transfer on a cylinder in a flow of combustion gases [31C], the flow field and heat and mass transfer around a cylinder in a pulsating flow [22C], the heat transfer from single solid bodies in high-temperature gas flow [20C], and the mass transfer from cylinders at different orientations to external stream [46C]. The axial heat-conduction effects have been theoretically studied in a forced convection situation along a cylinder [8C]. Calculations have been presented for the flow and heat transfer due to curved wall jets on cylindrical surfaces [26C].

The stagnation-point situation has been another topic of considerable interest. Measurements of transfer coefficients due to the impingement of initially laminar slot jets on a plane surface have been reported [38C]. Mean mass-transfer coefficients for a jet impinging on a surface have been measured by an electrochemical method [9C]. A correlation has been obtained for the stagnation-point heat transfer in ionized gases; the heat transfer is found to be proportional to the 0.7 power of the Prandtl number ratio across the boundary layer [4C]. An empirical correlation has been presented for the stagnation-point heat transfer on a cylinder in cross flow [12C]. The response of the thermal boundary layer in an unsteady stagnation-point flow has been studied by a new method [19C]. The fluid flow and heat transfer in an impinging slot jet have been analyzed for the case of a nonuniform velocity profile of the jet; the stagnation-point heat-transfer coefficients corresponding to the nonuniform velocity profile have been found to be about twice as large as those for a flat velocity profile [37C]. The problem of laminar heat and mass transfer at a three-dimensional stagnation point has been solved by the method of parametric differentiation [44C]. Saffman's turbulence model has been applied to the stagnation-point heat-transfer problem by analytical/numerical solution matching [42C].

Experimental results have been reported for a heated plane turbulent jet [10C]. The interaction between a boundary layer and an array of vortices has been studied analytically and numerically [30C].

## FLOW WITH SEPARATED REGIONS

### *Single bodies*

Fletcher, Briggs and Page [5D] review and classify more than 280 references dealing with heat transfer in separated and reattached flows. The most important factor [7D] that affects heat-transfer mechanisms in low speed, separated flows is the intensity of the vortices shed in the wake region. The shape of the front half of the object has little influence. By using the relationship between shear stress and turbulent energy similar to those discussed by Spalding [18D], a mathematical relationship is derived to predict heat transfer to the downstream stagnation region of a cylinder in cross-flow. For the classic case of a circular cylinder started impulsively, the distinction between vanishing wall-shear and separation is dramatic [24D]. By shaping, a novel boiler tube [19D] allows a combination of particulate pollution control without suffering any significant penalty in heat-transfer performance.

Flow in bounded mixing layers differs from simple unbounded jet and wake flows in that (1) the rate of growth of the momentum exchange layer is much smaller than in unconfined flows; (2) the rate of growth in the mass exchange layer is greater than in unconfined flows; and (3) the ratio of mass to momentum diffusion coefficients is substantially greater than in unconfined flows [22D]. The momentum transport coefficient at the center of a near wake is independent of the boundary conditions at a sharp trailing edge and of compressibility [27D]. Numerical studies of steady flows in two-dimensional cavities receive continued emphasis [17D].

### *Packed and fluidized beds*

Controversy has surrounded the subject of particle-to-fluid heat and mass transfer in dense systems of fine particles for the last decade. The problem is that experimental results are an order of magnitude below what everyone regards as a sound theory. A new theory [16D] recognizes that for low Reynolds number transport in dense beds, the stagnant limit ($Nu = 2$) does not apply. An analytical model is given [25D] for the convective heat transfer from a flat plate immersed in a flow granular medium. Fluid-to-particle heat-transfer measurements in a fixed bed were performed using microwave heating—resulting in a uniform bed temperature—thereby separating the fluid-to-particle heat transfer from the particle-to-particle mode [3D]. Heat transfer in porous sintered materials continues to be studied because of the efficient exchange [10D].

Experimental heat-transfer data using laminar flow of three different plastic disperse systems (an enrichment in the wall layer of the disperse medium) indicate no significant heat-transfer effect [6D]. McMillan describes the effect of deformation on the effective conductivity of a dilute suspension of drops in the limit of low particle Peclet number [13D].

Another "simplified" calculation method [12D] for the effective thermal conductivity and wall heat flux for packed beds is applicable to the case where the inlet temperature profile is not uniform. When the ratio of thermal conductivity of the discontinuous phase to that of the continuous phase is very large, there is a significant difference between prediction and experiment [29D]. [15D] presents experimental investigations of Newtonian, power law, and non-power law fluids in packed and fluidized beds. [26D] investigates the effective thermal conductivity of a fluidized bed with a packing. At a given Reynolds number, the fixed bed mass-transfer coefficients are always higher than the corresponding fluidized bed values [28D]. A general equation is proposed [20D] for predicting the minimum fluidization velocity of a mixture of particles of various sizes but all of the same shape and density. In [23D], the authors show that the complete set of describing equations for the idealized model of agitated vessels or fluidized beds can be solved analytically, "making numerical solutions for special cases superfluous". Another model [9D] of heat transfer in gas fluidized beds shows agreement with experimental data without recourse to any of the semi-empirical approximations of previous models. Rowe [21D] criticizes the data and correlation of [1D]. Heat transfer from a grid jet in a large fluidized bed [2D] is measured.

A model based on the simple two-phase theory of fluidization including catalyst particles as the third phase has been developed [4D] for a nonisothermal fluidized bed catalytic reactor with continuous circulation of catalyst particles. When spread over a finite thickness, distributed pressure drop is less effective in stabilizing a fluidized bed than when concentrated in a geometric plane [14D]. Finally, general papers on bed expansion [8D] and general fluidizing gas suspensions [11D] are available.

## TRANSFER MECHANISMS

Almost all work in the area of transfer mechanisms is concerned with turbulent flow. Experimental investigation and mathematical treatments have been reported.

There have been some theoretical studies of turbulence. The Euler equations have been solved numerically to simulate turbulence [3E]. Theoretical solutions for homogeneous turbulence with shear have been obtained and compared with experiment [6E]. A conventional statistical analysis of velocity and temperature fluctuations has been applied to the wall layers of a channel flow; the results have shown the presence of two intermittent phases [20E]. A statistical model for calculating turbulent temperature fields has been proposed; the validity of the model is limited to small Peclet numbers [11E].

Phenomenological models continue to be of considerable interest. A simple model has been developed for the prediction of turbulent flow over rough surfaces; the roughness elements are characterized by a form drag coefficient and a characteristic separation length [10E]. A phenomenological turbulence model has been applied to the fully-developed turbulent flow in rod bundles [14E]. The mixing-length distribution for turbulent boundary layers has been extensively examined by reference to experimental data; the constant of proportionality between the mixing length and the distance from the wall is found to vary with the pressure gradient [12E]. The mixing length in low-Reynolds-number compressible turbulent boundary layers has been derived from experimental data and is found to be higher at low Reynolds number [4E]. More than thirty ways of predicting the turbulent Prandtl or Schmidt numbers have been examined [15E]. A form of the turbulence dissipation equation has been obtained and applied to curved and rotating turbulent flows [13E]. A model has been presented which obtains the turbulence kinetic energy profile in the drag-reduction polymer solution flow in a pipe [19E]. The empirical constant in the turbulent viscosity expression for the Kolmogorov–Prandtl models has been examined and conditions have been established under which it can be regarded as truly constant [16E].

A number of investigations have included detailed measurements of turbulent flows. Measurements have been reported for: probability density functions for velocity and temperature in a round heated jet [18E], the local scales and intensity of density fluctuations in a supersonic jet [5E], velocity and temperature fluctuations in a heated jet [1E] and [2E], heat-transfer and temperature fluctuations in a high-Prandtl-number flow past smooth and rough walls [7E], and the flow of air through a grid with jets of air injected at the grid surface [17E]. Also, turbulence measurements have been made for the spanwise nonuniformity in nominally two-dimensional boundary layers; stable patterns of spanwise variations are identified [9E] and [8E].

## NATURAL CONVECTION

Interest continues unabated in natural convection studies. Emphasis is particularly placed on convection in enclosed regions, although there are many reports of studies related to boundary-layer flows and mixed (combined natural and forced) convection.

The problem of natural convection in a horizontal layer heated from below continues to draw the efforts of many researchers including those interested in stability, post-stability flow where non-linear effects begin to be important, high Rayleigh number flow where turbulent transport is of major interest and the influence of rotation and magnetic fields as well as flow in porous media.

Calculations for the critical Rayleigh number in heated from below enclosures yields better values for lower bounds of the critical Rayleigh number in arbitrary configuration [74F]. Both upper and lower bounds on critical Rayleigh number have been obtained for vertical and axial cylinders and cones [75F]. The onset of convective flow after a transient has been analyzed [67F] and measurements have been made following a step change in the heat flux [29F] in a horizontal layer of air heated from below. The finite amplitude in stability for an initially homogeneous two component fluid has been examined [73F].

Fluctuations near the convection threshold in a heated from below system have been described [33F]. A numerical simulation of cellular convection shows a series of transitions in both heat flux and flow pattern that depend on Prandtl number of the fluid [96F]. Finite amplitude convection in a bounded cylindrical layer with conducting walls has been analyzed [12F]. The effect of side walls on convection has been analyzed for free upper and lower surfaces [20F].

An approximation to the non-linear equations for high Rayleigh number convection gives the asymptotic dependence of Nusselt number on Rayleigh number and Prandtl number [32F]. Measurements of the heat transport in a horizontal layer heated from below have been made up to a Rayleigh number of $2 \times 10^9$ using gaseous helium at low temperature [93F].

An empirical fit of heat-transfer data indicates an asymptotic approach of Nusselt number varying with the Rayleigh number to the one-third power at large Rayleigh number [40F]. Models on the release of thermals from the edge of the boundary layer have been postulated for the heat transport in thermal convection [18F]. The flow produced by non-uniform temperature in a buoyant mass is considered in a study on the initial rise of a thermal [36F]. Motion of a localized region of hot fluid—a thermal—is analyzed to determine the entrainment rate of the thermal [85F].

Heat transport in horizontal fluid layers with distributed energy sources within the layer has been studied recently with application to nuclear reactor safety. The instability of such layers has been analyzed for a variety of boundary conditions [49F]. Measurements on such a layer with an insulated lower boundary layer have been conducted up to a high Rayleigh number [50F]. Heat transfer with uniform energy sources as applies to a molten $UO_2$ layer has been analyzed [90F]. The effect of dissipative heating in convective flows is considered with applications to geophysical phenomena [38F].

Simultaneous velocity and temperature measurements indicate the major contribution to flow in turbulent convection in water over ice comes from plume-like masses [2F]. Measurements of melting over a layer of ice heated from above indicate a critical Rayleigh number for the onset of flow of about 500 [89F]. Numerical simulations of convection in water cooled from above near the ice point have been performed [27F]. Optical measurements have been reported in a study on the freezing of sea water [26F].

A number of investigators have considered thermal convection in porous media. A binary gas mixture in such a medium is found to have a lower critical Rayleigh number than a single component gas [52F]. A magnetic field is found to inhibit the onset of flow in porous media [77F]. The instability in a porous layer saturated with a heat generating fluid has been examined [51F]. Convective currents have been studied in a porous layer [66F] and at high Rayleigh numbers, Darcy's Law is found to be invalid in cellular convection [83F]. In a tilted porous layer, at low Rayleigh numbers, the heat transport is found to be a function of the product of the Rayleigh number and the cosine of the angle from the horizontal [98F]. In a vertical porous layer, the effects of variable viscosity on convection have been studied [99F].

The effect of rotation on the velocity in Benard convection has been analyzed [62F]. Convection in layers heated from below with rotation in the presence of a magnetic field has been studied, including the effect of a rotating magnetic field [81F] and the stability of a fluid layer in a uniform magnetic field [24F]. The inhibiting nature of a magnetic field on convection has been demonstrated [7F]. Velocity and temperature fields have been measured in a rotating layer [58F]. Another experimental study examines centrifugally driven free convection in a rectangular cavity [1F].

Other studies in closed regions have been made for a variety of geometries. Within a single horizontal cylinder an experiment on transient heating shows that above a certain Rayleigh number the time for heating the fluid is independent of Rayleigh number [37F]. Different quasi-steady modes of convection have been predicted in the cooling of a horizontal cylinder of water through its maximum density point [30F]. Quasi-steady heat transfer has been obtained in natural convection inside a sphere [13F].

The laminar motion in a closed container following a step change of temperature of the walls has been calculated [46F]. Visualization of the flow between a body and a spherical enclosure demonstrates the presence of various flow regimes [76F]. Varying flow patterns are observed with natural convection in a horizontal annulus containing water with the maximum density point occurring within the container [84F].

The critical Rayleigh number in a vertical cylinder is found to be relatively independent of the diameter to height ratio above a value of about three [88F].

Results from experiments on convection in an inclined rectangular channel agree with analytical predictions [70F]. The numerical solution for thermal convection in a rectangular enclosure with the side walls at different temperatures has been described [87F]. The upper surface boundary condition has an important influence on the flow structure within a shallow cavity with differentially heated end walls [16F].

Experiments on natural convection in vertical layers include measurement of unsteady free convection in air spaces [43F] and steady local heat-transfer measurements over a range of gas pressures [21F]. Temperature fluctuation has been studied [95F] in the transition to turbulent flow in a vertical layer. Different regimes of heat transfer are postulated in air filled cavities [19F]. Numerical experiments indicate the effect of lateral temperature gradient in a narrow vertical slot [101F]. Correlations for heat transfer to normal fluids are found to be valid with certain non-Newtonian fluids heated in vertical enclosures [25F]. Experiments with low Prandtl number fluids include natural convection in a vertical channel [42F] and in an array of uniformly heated vertical cylinders [22F].

An annular thermosyphon has been proposed for maintaining permafrost in cold regions [79F]. Introduction of air bubbles in a thermosyphon aids the natural liquid circulation [54F].

Natural convection over a horizontal surface is studied using as an analog a two-dimensional wall jet [94F]. Optical and electro-chemical studies of natural convection from a horizontal surface show different flow modes which can strongly influence the transfer rates at different Rayleigh numbers [71F]. Turbulent transport has been analyzed in a thermally stratified boundary layer with application to fog formation over ocean surfaces [72F].

Natural convection on upward and downward facing inclined constant heat flux surfaces has been studied [97F]. In another study on downward facing inclined surfaces, the use of the component of gravity parallel to the surface is found to adequately predict local mass-transfer coefficients [60F]. The breakdown of laminar natural convection on an inclined plate occurs with a thermal wave initiated near the plate surface [5F].

A sequence of functions has been determined [10F] which can be used to obtain local similarity solutions for natural convection boundary layer flows. The laminar boundary-layer heat transfer on a vertical plate has been studied, including the effects of immersion in a thermally stratified fluid [91F] and of a variable coefficient of volumetric heat expansion [6F]. The prediction of turbulent transport along a vertical flat plate has been analyzed using an eddy viscosity formulation [9F, 68F].

The characteristic disturbance frequency which is amplified in a vertical natural convection flow is found to be only a function of Prandtl number [28F]. Simultaneous heat and natural convection mass transfer in an electrochemical solution has been obtained [82F]. Empirical equations for correlating laminar and turbulent convection from a vertical plate [14F] and from a horizontal cylinder [15F] have been described.

Optimization of natural convection heat transfer from fins has been applied to the cooling of electronic equipment [69F]. Optimal plate spacing, to have minimum temperature difference between fins and surrounding air for natural convection from vertical flat plates has been measured experimentally [53F].

Measurements of the circumferential variation of heat transfer around a horizontal cylinder agree well with earlier integral analysis except near the top of the cylinder [48F]. Flow visualization shows different regimes of flow on a horizontal vibrating isothermal cylinder [8F]. A numerical solution has been presented for natural convection in a boundary layer on a cylinder with blowing and/or suction [59F]. Detailed flow and temperature measurements are described for natural convection near the top of a heated hemisphere [44F].

A number of studies have been concerned with plumes involving line sources or point sources. Asymptotic solutions have been obtained for slightly buoyant laminar plumes above a point and line source [100F] and above a point source immersed in a fluid at low Prandtl number [17F]. Higher order boundary-layer effects were included in laminar flow above a line source [39F] while a plume model for convection in the atmosphere has been extended [92F] to include compressibility effects. Amplification of naturally occurring disturbances below a cutoff frequency leads to a transition of a plane natural convection plume [4F].

Measurements of plumes above line sources include the velocity distribution determined with a laser–Doppler apparatus [31F]. The plume above a line source close to a vertical wall entrains less then half the flow of a plume above a similar source away from a wall [34F].

In combined or mixed convection, the effects of natural convection are superimposed on a forced flow. In certain instances, the natural convection flow may be the dominating one, while in others the forced flow may be the major contributor to the overall flow and heat transport. Mixed convection is often important in internal flow systems. A finite-element analysis of combined natural and forced convection laminar flow through a vertical duct yields specific results for flow in square and triangular ducts [65F]. The Nusselt number in mixed flow in a vertical duct is found to be relatively insensitive to the inlet conditions [23F]. Another study considered aided flow in a vertical annulus [56F]. A significant increase in heat transfer is found when natural convection is imposed on a laminar forced flow in a horizontal tube [61F]. The circumferential variation of the heat flux with mixed convection in a round tube was measured [47F].

The effect of buoyancy on an MHD forced convection flow in a horizontal channel has been examined [45F]. Significant effects of natural convection were found during flow of whole blood in thin channels [41F]. Combined natural and forced convection on a vertical plate has been studied with aided convection on an isothermal plate [35F] and with opposed flows on a mass-transfer plate [80F]. Natural convection effects on the oscillatory flow past a vertical plate with suction have been analyzed [86F]. Aided flow along a circular cylinder has been studied [11F] including the effect of cylinder radius on the heat transfer.

The buoyancy effects on heat transfer to a micropolar fluid in a horizontal parallel-plane channel have been examined [55F]. Buoyancy effects in a horizontal flat-plate boundary layer have been studied on the floor of a 28-m long wind tunnel test section [3F]. Heat transfer from a horizontal circular wire has been measured including the cases of pure forced and free convection [63F] as well as mixed convection with parallel, opposed and cross flows [64F].

An experimental study of heated buoyant jets discharged into water includes the variation in temperature at the water–air interface [78F]. Following injection of gas into a container, different heat-transfer regimes are present depending on the time relative to the injection [57F].

## CONVECTION FROM ROTATING SURFACES

Several papers consider heat transfer from a rotating disk either shrouded by a stationary disk at a short distance or in an unlimited environment. An analytical and experimental study [3G] considers the radial outflow of air as a coolant at rotational Reynolds numbers between $5 \times 10^5$ and $5 \times 10^6$. Local heat-transfer coefficients on a rotating disk in still air were measured [6G] over a Reynolds number range from $10^4$ to $10^6$. Resulting Nusselt numbers are presented as a function of $(Gr+Re^2)^{0.5}$. The temperature field of the cooling air flowing radially outward was calculated [7G]. Mass-transfer experiments using naphthalene disks were interpreted through the heat-transfer analogy to obtain heat-transfer coefficients [4G]. Experiments for Reynolds numbers between 19000 and 51 000 demonstrated that transpiration cooling reduced heat transfer on the rotating disk [2G]. Ratios of heat-transfer coefficients with and without transpiration cooling ranged between 0.21 and 0.69.

The temperature field and local heat transfer were measured in a cavity formed by a rotating disk, a stationary disk, and a stationary cylindrical enclosure, with cooling air injected through the rotating disk and removed through the annular space between this disk and the cylindrical wall [8G]. Strong rotation was found to create substantial local variations of the fluid temperature throughout the cavity.

An analysis [1G] studies the effect of centrifugal and Coriolis forces on convective heat transfer of a liquid flowing through a tube rotating around its axis. A computer calculation [5G] studies laminar heat transfer of a fluid flow through a rotating eccentric annulus. The circumferential variation of the Nusselt number was found to be strongly reduced by a modest swirl up to eccentricities of 0.5. Nusselt numbers are raised to twice the friction factors for fluids with $Pr = 0.7$ [5G]. It is suggested that the same effect might be obtained by helical ribs inserted into a tube.

## COMBINED HEAT AND MASS TRANSFER

Film cooling continues to be of interest to a number of investigators. For gas injection through a row of holes on the film-cooled surface, no simple correlation is found for experimental results obtained over a range of density and velocity ratios of the injected fluid [7H]. Experiments with a two-dimensional array of holes indicate the film effectiveness and heat transfer for such flows [14H]. Little effect of Mach number is observed up to a value of approximately 0.9 for film cooling from a row of holes, at an inclined angle of 30° [9H]. An infrared technique has been used to measure the local film cooling downstream of discrete injection [1H].

An experimental study of the flow characteristics of multiple jets directed into a cross-flow should give information which is helpful in understanding three-dimensional film cooling [21H]. Analysis of the behavior of a turbulent boundary layer with discrete jets also has application to film cooling [8H].

Other studies have examined the influence of various parameters on film cooling following injection through a two-dimensional slot. Downstream of the slot a region of separated flow is present at high blowing rates reducing the film cooling effectiveness and increasing the heat-transfer coefficient [6H]. A heat sink model has been used for prediction of the heat transfer with two-dimensional film cooling [19H]. Cross-flow with slot film cooling at Mach 4 yields very non-uniform film cooling protection [17H]. A study of oblique slot injection in high speed laminar flow [16H] shows that injection normal to the main flow can provide better cooling than tangential injection. A study of the mass transfer [3H] from a gas liquid film interface has application to liquid film cooling.

Several studies on flow and heat transfer in capillary bodies were contributed by Russian engineers. One [10H] reviews the mass transfer in capillary porous systems. Two-phase flow has been studied in porous walls to predict stability and the characteristics for transpiration cooling systems [11H]. Two other studies [12H, 13H] also consider the stability of such flows. Numerical solutions [23H] and experiments [22H] are provided to help understand the heat and mass transfer in a honeycomb catalyst. An experimental study on the heat and mass transfer between a catalyst and a stream of the reactant gas has been reported [4H].

Cooling from a circular jet impinging on a surface after passing through a cross-flow has been studied experimentally [2H]. For large blowing rates, maximum cooling occurs when the surface is about five diameters from the entering jet [20H].

The drying of a layer of moist material in contact with a hot surface has been analyzed [15H]. The motion of a single evaporating droplet has been studied including the effects of varying heat transfer [5H]. An analytical study [18H] presents solutions for the cooling of liquid drops in a hot gas flow.

## CHANGE OF PHASE

### *Boiling*

Much important work is being done on the liquification of natural gas. In such plants, heat exchangers are the bulk of the equipment. Hence the development of efficient heat exchangers, particularly evaporators, is of practical importance [28J]. One form of evaporative cooling that has potential industrial application for localized cooling is the boiling of a liquid jet impinging on a high temperature surface [60J]. Data on boiling on surfaces with non-metallic materials ($k < 3\,\mathrm{W/m^2\,°C}$) show that the heat transfer depends significantly on the thermal conductivity of the coating material. These tests [85J] include scale and other boiler deposits. Using laser interferometry, [83J] finds the microlayer thickness is of the order of $5\,\mu\mathrm{m}$ and microlayer evaporation represents 25% of the total nucleate boiling heat-transfer rate. Two other papers deal with evaporation microlayers [80J, 81J]. The effects of Jakob number on forces controlling bubble departure [62J] are obtained qualitatively. In evaluating the microlayer contribution to bubble growth it appears appropriate to assume the bubble shape is represented by a spherical segment characterized by a base radius $R$ [63J]. The behavior of a nucleate bubble is controlled not only by its dimensions but also by its algebraic rate of growth at the time of nucleation [17J]. In describing the influence of gas bubbles on heat transfer in two-phase gas liquid systems [29J], transient conduction into the liquid is the predominate mode of bubble induced heat transfer and is responsible for about 75% of the heat transfer. Convection contributes the remainder. A new [65J] bubble similarity analysis leads to self-similar dependence of bubble radius in three cases: (1) when the liquid pressure is constant; (2) when it varies slowly with time; and (3) in an ultrasonic field. Reference [76J] also deals with the computation of the average growth rate of vapor bubble using similitude. Supplementing the drift current theory, the flow and temperature fields in the liquid behind a rising bubble are solved numerically using a finite difference method [3J]. Reference [19J] deals with the troublesome problem of interfacial area in bubble layers.

Labuntsov [33J] summarizes current theories of nucleate boiling of liquids. A new model of bubble growth results. A correlation to determine the initial point of net vapor generation IPNVG is given [79J] for water and Refrigerant-22 along with a scaling law to predict this point for other liquids. In [35J] the influence of the thickness and thermal properties of heating walls in nucleate pool boiling is reported. Measured active cavity radii agree with the active cavity radii predicted by the Hsu model [66J]. Reference [34J] describes a gas diffusion technique for determining pool boiling nucleation sites. In this method, the cavity is not given the same rigorous test of stability that is associated with real nucleate boiling. Even marginally stable cavities may remain stable. Harstad [21J] examines nonstationary homogeneous nucleation. Experimental growth of bubbles using high speed photography is becoming commonly accepted. In [18J] these data are coupled with the continuous temperature distribution around a single bubble that is obtained by changing the position of a thermocouple probe and analyzing a large number of bubbles.

Reference [54J] extends Reynolds flux predictions of critical heat flux to rod bundles with non-uniform heat flux. Burnout with boiling salt water in the tubes is investigated [84J]. The vertical distribution of longitudinal heat flux release is sinusoidal in nuclear reactor cases. $q_{cr}$ (sin) are generally lower than $q_{cr}$ (constant heating)—as much as 80% smaller [51J]. The effect of a helical insert on boiling heat transfer is investigated with no perceptible effects [16J]. The application of swirl can increase or decrease $q_{cr}$, depending upon mass-flow rate, pressure, and distance from swirl generation [50J]. The spectral analysis of the noise that accompanies boiling can be used for recording the time of onset of critical heat flux density [27J]. Reference [77J] studies boiling crisis generated upon a steep increase in power in heaters with different tube wall thicknesses.

Contrary to expectation, the diffusivity of the hot surface is not a controlling factor in the Leidenfrost point [13J]. The transition from column boiling to sheet boiling in $CO_2$ in the two-phase region below the critical point is studied [2J].

Two papers by Reimann and Grigull [56J, 57J] analyze natural convection and film boiling in laminar boundary layers with temperature dependent properties. Moreaux *et al.*, deal with destabilization of film boiling by means of a thermal resistance [42J].

A complete analytical model is developed [23J] to describe the sequence of transient events associated with a hot sphere moving into a cool liquid where a vapor blanket surrounds the sphere—a vapor explosion. Two papers [9J, 10J] deal with transient boiling of liquified cryogens on a water surface. Film boiling from a partly submerged sphere is carried out [37J]. In a related paper [59J], the pressure excursions accompanying the transient film boiling which occurs when a large pool of saturated and stagnant liquid is suddenly exposed to a very hot solid sphere is analytically evaluated. Actually, very few experimental studies have been made on film boiling with significant degrees of subcooling [11J]. No complete answer yet exists for the problem of predicting the collapse of forced convection film boiling—referred to as surface rewet [25J]. More exactly, surface rewetting refers to the phenomenon of establishing liquid contact with a solid surface whose initial temperature is greater than the rewetting temperature.

Reference [75J] gives an analytical solution to the falling-film rewetting problem. Reference [46J] analytically describes evaporation of a laminar falling liquid film along an inclined wall. Taylor's theory of instability of waves as applied to film boiling [55J] does not yield any tangible solution to the problem of predicting the effect of interfacial shear on evaporation rates of liquid patches. The von Karman analogy between heat and momentum transport in turbulent flow is shown to apply [6J] to heat transfer through wavy liquid films in horizontally stratified, gas–liquid flows. A contribution which helps clarify the physical processes in the evaporating part of a film-evaporation combustion chamber is presented [68J]. Reference [39J] explores evaporation of liquid nitrogen droplets on metal surfaces. Development of an analytical model and a technique for predicting droplet lifetime in the critical region will require further information on droplet vaporization dynamics [36J]. In [47J], design variables for attaining minimum evaporation rates by properly varying the cross section of ducts transporting gas droplet flows are investigated for low concentrations of droplets. Considerable sophistication in property variations can be built into an analysis of droplet evaporation phenomena [32J]. The ebullition rate of superheated drops in an immiscible liquid was found to be proportional to the initial area of a drop and to increase with rate of temperature rise [43J]. The problem of heat and mass transfer around an evaporating water droplet in a superheated steam flow is studied [41J] using singular perturbation methods. In [24J] a comprehensive numerical study of the effects of transients and variable properties on single droplet evaporation into an infinite stagnant gas is given. Comparisons of solutions using various reference property schemes with those for variable properties results in recommendations concerning a suitable reference state and quasi-steady constant property solutions.

Heat transfer of a gas flow over an evaporating liquid surface is found to be higher than on solid surfaces [26J]—a result apparently due to the rise of turbulence intensity in the turbulent boundary layer. Bhatti and Savery [5J] also discuss augmentation of heat transfer in a laminar external gas boundary layer by vaporization. With boiling in a tube of unsaturated solutions of different impurities, evaporation leads to an increase in their concentration in the wall layer; this may cause an increase in corrosion as well as lead to formation of deposits on the heat-transfer surface [4J]. Dimensionless evaporation rates of liquid nitrogen tetroxide into flowing high pressure air or helium depend on Reynolds number [72J]. A single fin analysis can be used to predict the boiling of liquids in a compact plate-fin heat exchanger [52J]. Reference [20J] gives an overview of several experimental investigations of heat-transfer mechanisms from finned or corrugated tubes to various boiling liquids. Heat transfer increases 3–4 fold are found in a thin film evaporator employing longitudinal finned tubes [58J]. Although the feedwater flows primarily in the depressions between the fins, the thin film is continuously replenished on the projections due to splashing.

### *Condensation*

The condensation coefficient of mercury on a clean surface of liquid mercury was measured by a molecular beam method to be between 0.65 and 1.0 [48J]. To determine the rate of condensation of vapors from binary gas mixtures flowing in a tube under reduced pressure, the equations for high and low vapor concentration are compared with experiment [44J]. The variation of temperature driving force over the perimeter and height of horizontal and vertical tubes is included in an analysis of condensation of binary mixtures and vapors of immiscible liquids [64J]. The total condensation of mixed vapors forming a homogeneous liquid phase is a case more often encountered in practice than condensation of single vapors [1J, 82J]. In [1J] experimental studies of heat transfer on a horizontal tube of binary and ternary vapors of miscible liquids are presented.

Epstein and Cho [14J] obtain simple, closed-form solutions to laminar film condensation with heat generation using Nusselt's method. In [71J] film condensation heat transfer on inclined surfaces (0.1 1.0 g) was higher than predicted by Nusselt's correlation. Marschall and Hall [38J] describe experiments on binary, gravity-flow film condensation on vertical isothermal plates. Elliptical tubes aligned horizontally are economically more promising for condenser evaporators than classical vertical arrangements [40J]. The optimum ratio of vertical to horizontal axis is about 4.0. When the molecular weight of a noncondensable gas is smaller than that of the condensable there will be an unfavorable buoyancy effect which tends to retard the flow of vapor condensing on a vertical wall [61J]. Two papers, [12J, 45J], analyze laminar film condensation heat transfer in the presence of electric and magnetic fields. Heat transfer with film condensation on a sphere is extended to account for liquid wetting [53J]. Steady state solutions can be used to predict quasi-steady condensation effects as long as the dimensionless thermal diffusion time constant for the film is small [7J]. Tanaka gives a comprehensive theoretical study [73J] and confirming experiments [74J] of dropwise condensation suitable for design applications. There is a great lack of experimental data on direct contact condensation of droplets falling in airstream mixtures. The available data for pure steam and of the range low void fraction are widely scattered [30J].

### *Two-phase flow*

Analysis of the effect of cooling ahead of the wet front in falling film rewetting was reported [70J]. Cubic interpolation of the time dependence of the temperature of a solution droplet in high temperature drying is used for calculating the average droplet temperature over this period [8J]. The effect of the design features of the U-shaped thermosyphon on its performance is analyzed [69J]. A small disturbance propagating in a gas-liquid two-phase bubble flow in which bubbles are of the same component as the liquid is analyzed [22J].

When cylindrical ice melts in a cylindrical radiative heater where both natural convection and radiation exist, it is difficult to determine the exact solution for the ice fusion due to interacting effects [49J].

Thermal explosion occurs when molten copper particles attain the solidification temperature and the heat transfer on its surface is sufficiently intense. The sharp-change of the crystalline structure during the solidification of the molten metal is the cause of the explosive fragmentation [86J].

Reference [31J] deals with the liquid film stability for a counter-current annular two-phase flow in which a liquid film flows down along a wall of the vertical tube and gas flows up in the core.

The versatility of static mixers has been recognized in recent years. The Koch mixer is the latest design and is suitable for use in an aeration or oxygenation system [15J].

In the desalination of sea or brackish water by freezing, the size distribution and shape of the ice crystals growing in the turbulent brine solution are determined by their local environment and surface kinetics [67J]. If a freezing technique is to be of any clinical value, it must avoid the formation of intracellular ice supercooling should be minimized [78J].

## RADIATION

### *Radiation in participating media*

Radiative transport in emitting, absorbing and scattering gray and non-gray media continues to attract substantial interest. Effects caused by simultaneous conduction or convection are frequently included. A new scheme for the efficient calculation of longwave radiative heating rates in the lower part of the earth's atmosphere is substantially more accurate than previous approximations [17K]. A method based on a direct numerical solution of the spherical harmonics approximation to the radiative transfer equation for the atmosphere can be used for obtaining smooth scattered-intensity angle-of-observation curves for any arbitrary position of the sun [12K]. The iteration scheme proposed by Chahine for the solution of the radiative transfer equation is discussed in the context of the inverse problem for the thermal structure of the atmosphere [5K]. A method is proposed for estimating the vertical transmission of radiation through horizontally non-homogeneous media (atmosphere) [2K].

Errors associated with discontinuities in radiative transfer analysis can sometimes be greatly reduced by careful selection of the quadrature order if Gaussian quadrature is used for solving the equation of radiative transfer [39K]. Closed form exact solutions are presented for radiative transfer in emitting–absorbing, non-isothermal media bounded by cylinders (finite and infinite) or concentric cylinders with prescribed three-dimensional temperature distribution over these surfaces [15K]. The same type of calculation is performed for obtaining exact solutions in non-isothermal spherical media [10K].

A new method is proposed for the calculation of the optical constants of weakly absorbing thin films. Results are given for various materials in the near-UV and visible regions of the spectrum [25K]. For solar collectors selective coatings are of particular interest. Through a study of spectral and directional radiation characteristics of thin-film coated isothermal, semi-transparent plates some potential candidate materials have been identified and the spectral transmittances and reflectances of these materials have been predicted

[35K]. The evaluation of flat-plate solar collectors requires knowledge of the transmittance and absorptance of a series of parallel regions with different radiation properties. The net radiation method is utilized for developing expressions for such configurations in terms of the effective transmittance and reflectance of the individual regions [40K]. A simplified, approximate method is presented for calculating the effective emissivity of non-isothermal, diathermanous coatings [3K]. Directional and hemispherical reflectance and transmittance resulting from collimated incident radiation on a semi-infinite absorbing–scattering medium are presented as a function of refractive index and scattering albedo. For normal incident radiation hemispherical reflectances are within 15% of the predicted values [4K]. Substantial errors involved in reflectance measurements of highly transparent substances are mainly due to the non-blackness of backing materials [19K].

A general solution of the radiative transport equation is presented applicable to a wide range of problems involving radiative transport in absorbing, emitting, and anisotropically scattering media with arbitrary, but specified temperature distribution [32K]. Considering compressible boundary-layer flow over an adiabatic flat plate, scattering reduces the effect of radiation shifting the temperature profiles towards those found for the non-radiating case [7K]. Approximate analytical solutions are obtained for the equations of radiative transfer in spherical and infinite cylindrical light-scattering media with uniformly distributed radiation sources [1K]. The effects of radiative attenuation and scattering are studied in plane and spherically symmetric media containing metallic, opaque particles [41K]. Relationships are derived for the propagation and attenuation of radiative fluxes in multi-layer systems of selectively absorbing and scattering materials with variable optical properties [21K]. The results of heat-transfer studies in a gray planar medium with linear anisotropic scattering reveal the importance of anisotropic scattering on heat fluxes and incident radiative fluxes [13K].

Based on explicit matrix formulae derived for the calculation of total exchange areas, working relations are established for the heat transfer in uniform gray absorbing–emitting, isotropically-scattering media confined in a Lambert enclosure [31K]. Two-dimensional temperature and heat flux distributions are calculated for an absorbing–emitting gray medium in radiative equilibrium in a rectangular enclosure. Comparison with some numerical solutions generated by Hottel's zonal method shows excellent agreement [28K]. The influence of spatial fluctuations in the incident radiation on the flux at the boundaries of a two-dimensional, finite, planar, absorbing–emitting, gray medium is reported considering both collimated and diffuse incident radiation [8K]. Measurements of local characteristics of the radiation field in a cylindrical air medium confirm analytical results which predict little variation of the radiant flux within a given cross section [37K].

It is shown that a general slab band absorptance formulation for infrared radiating gases is valid for a wide range of pressures and optical depths [26K]. An analytical solution for a planar non-gray medium in radiative equilibrium is found to be valid for all optical thicknesses with an error less than 0.5% compared with existing numerical solutions [27K]. Numerical results of studies of non-gray radiative transfer in a semi-infinite medium in radiative equilibrium show that the absorption coefficient consists of an array of equal intensity, non-overlapping bands of lines [11K].

A general formulation for radiative heat-transfer calculations based on integrated emissivities and absorptivities is useful for combustion chamber calculations where the active medium consists of gases such as $H_2O$, $CO_2$, and soot [24K]. A three term gray-gas model is suitable for the description of the emissivities of $CO_2$–$H_2O$ soot mixtures in nitrogen for a wide range of temperatures and soot concentrations [34K]. For determining the infrared radiative properties of $H_2O$, $CO_2$, and $NH_3$ these molecules are excited by a single high-energy collision with $N_2$, O, or argon [16K]. Shock tube measurements are reported of the emission of $CO_2$ around 2.7 μm at temperatures of 2400 and 3500 K [20K].

The optical constants of ordinary glasses measured in a range from 0.29 to 4000 $cm^{-1}$ at 293 K show an intense absorption coefficient spectrum reaching a peak value of approximately 1500 neper/cm with a spectral width at half peak of 950 $cm^{-1}$ [6K].

Possibilities and limitations are discussed of using the uncoupled superposition approximation for combined conduction-radiation through IR radiating gases [29K]. Studies of coupled thermal radiation and heat conduction in a medium with a spectrally dependent mass absorption coefficient for a wide range of parameters demonstrate that exponential and gray band results differ considerably in both a qualitative and quantitative sense [30K]. An analysis of steady, one-dimensional heat transfer through a gray radiating–conducting semi-infinite space bounded by a flat plate kept at constant temperature reveals that thermal conductivity has little effect on the temperature distribution with exception of a thin layer adjacent to the plate provided that heat transfer by radiation dominates [22K].

Studies of the transient temperature distribution in radiatively heated infrared transmitting chalcogenide glass confirm the special characteristics of this type of glass as IR window material. The rate of temperature rise and temperature differences are small compared with soda–lime glass [23K].

Investigations of radiation-induced thermal stratification in surface layers of stagnant water show good agreement between measured and predicted temperature profiles, thus verifying the radiation and total energy transfer models in stagnant water [33K].

Combined radiative and convective heat transfer are analyzed, considering the flow of a radiating gas over a flat plate or a cone assuming that the effect of scattering, the radiation density, and the radiation pressure are small and that the Schwarzschield–Schuster approximation for the plane layer holds [18K]. The effects of natural and forced convection in an emitting–absorbing gas flowing in a vertical channel are analyzed. The spectral variation of the radiative properties is included through the use of the total band absorptance and specific numerical results for the 15 μm band of $CO_2$ are reported [14K]. Studies are reported of simultaneous non-gray radiation and thermal diffusion in a thermally and hydrodynamically established laminar or turbulent pipe flow with uniform internal heat generation. The radiative Nusselt number increases almost linearly with the radiation to molecular conductance ratio and also linearly with the optical depth $\tau_R$ at small $\tau_R$ and logarithmically at large $\tau_R$ [38K].

The time variation of the radiation intensity behind a shock-wave in air may be correlated to the shock-wave attenuation rate in a shock tube and boundary-layer effects on particle flow time [9K].

Stagnation temperatures derived from the emission spectra of excited HF molecules of a $SF_6$–He continuous-wave HF supersonic diffusion laser are 10–30% higher than those predicted from plenum pressure and mass flow rate. This result is a consequence of heat losses to the wall of plenum and throat which are not considered in the predictions [36K].

### *Surface radiation*

An empirical expression used in shape factor reflection analysis was modified [3L] to account for reflection far from diffuse. Local and integrated emissivities were calculated [1L, 2L] for cylindrical cavities with a circular diaphragm and a plane or conical bottom. The emissivity was found to increase rapidly with decreasing opening of the diaphragm and with decreasing cone angle. Simple rules were obtained connecting the emissivity for nonisothermal and isothermal cavities for spectral and total radiation. Radiative heat transfer was studied for infinite rows of gray cylinders and for semi-infinite rows of black cylinders [4L].

An analysis studied radiation effects on heat transfer [5L] in the reactor core and in the heat exchangers of high temperature nuclear reactors operating with helium.

## LIQUID METALS

Local and mean turbulent transport properties for liquid metal heat transfer in an equilateral triangular rod array [4M] were based on the eddy distributions in various directions calculated from a phenomenological turbulence model. The total energy transport turned out to be larger than that obtained by adding conduction and turbulent transfer. Two analyses [1M, 6M] calculated the effect of the growth of vapor bubbles on the degree of superheat in a liquid metal. Experimental results [2M] are reported for sodium pool boiling. The condensation of metallic vapor in free turbulent jets through molecular aggregates and particles was analyzed [5M]. Some disagreement with experiments using silver vapor are discussed and explanations offered. Explosive boiling of superheated liquid metal was established [3M] as the main factor determining the disintegration of an exploding wire.

## MEASUREMENT TECHNIQUES

Topics of major interest in the area of measurement techniques include laser–Doppler anemometry, holography, hot wire (and hot film) anemometry, flow metering, temperature measurement, pyrometry, and devices for measuring thermodynamic properties of substances.

Interest continues in laser–Doppler anemometers (LDA) with major efforts in improving their accuracy, extending their range and using various signal processing techniques to obtain and analyze data. A signal-to-noise calculation provided a direct comparison between various arrangements of a LDA [56P]. The optimization of a LDA with regard to scattering center size, laser parameters, and photoreceiver aperture was found by using Fourier optics [20P]. A correlation technique was evaluated for use with a LDA to perform evaluations of highly turbulent flows [12P]. The measurement of turbulence frequencies up to 4 kHz is made possible by processing LDA signals using sampling spectrum analysis [58P]. The use of a superheterodyne spectrum analyzer offers the possibilities of extending the analyzable spectral range and determining the sign of measured velocities [42P]. Another data acquisition system for LDAs is described [46P] with which the velocity distribution data may be printed out, graphically displayed, or computer processed.

Laser–Doppler anemometers have been applied to a number of problems in the laboratory and in the field. Combining a fiber optic catheter with a LDA facilitates the measurement of blood velocities in vessels or in tubes [63P]. Velocities up to 200 m/s in condensing steam flows with wetness fractions at least as high as 0.05 can be measured without artificial seeding [17P]. Air speed measurements of an aircraft can be made up to an altitude of 3000 m with an error of less than 0.5% using a $CO_2$ LDA [48P].

Other optical measurement techniques such as holography and interferometry have been investigated. In many cases, optical data can be corrected using approximate methods for calculating refractive errors in schlieren, shadowgraph, interferometric and holographic determinations of transport phenomena [3P]. Holographic interferometry was successfully applied to a large-scale wind tunnel experiment to evaluate three-dimensional density fields around opaque bodies [71P]. Measurements of two velocity components were achieved using a single Fabry–Perot interferometer and photodetection system [22P]. A fairly large spread was observed in early determinations of laminar and turbulent velocity profiles using air-flow-birefringence measurements [14P].

Developments in hot wire and hot film anemometers have been reported. A two-wire probe followed by a new, simpler electronic analog circuit was devised in order to provide simultaneous velocity and temperature signals in turbulent air flow [1P]. Simultaneous variation of the gain of the servo amplifier and the mean wire temperature in a hot wire anemometer resulted in a nearly constant frequency response for useful ranges of both overheat and flow conditions [69P]. A technique which uses an oscillating hot wire anemometer probe traversing a flow in a direction perpendicular to the mean flow provides a means to directly measure the first and second spatial velocity derivatives [8P]. For turbulence intensities greater than 30%, an X-probe can lead to significantly large error, the error in one correlation being 28% when the turbulence intensity is 35% [65P]. It was shown that the usual techniques of sum and differencing of hot wire anemometer signals to calculate turbulence properties may not be valid when the flow is two-dimensional [21P].

A number of papers were concerned with flow meters. The calibration of rotometers was described in [51P]. Typical tolerances on the sharpness of the inlet edges of purchased orifices can result in one to two percent variations in their actual discharge coefficients [11P]. The authors of [70P] recommend that both pipe wall tap and throat tap nozzle installations be considered as equally accurate for use in precision flow metering work. Currently used correlations for two-phase flowmeters all show similar and predictive reliability [60P].

Various other approaches of measuring flow conditions have been reported. A shear-stress meter was described for measuring the horizontal momentum in the atmospheric boundary layer [18P]. The authors of [6P] provided a general discussion of some methods of measuring flow of solid particles dispersed in a gas medium, by observing the electrical conductivity of the flow. A velocity calibration unit for thermistor probes was described [23P]. Velocity measurements can be made in a separated boundary layer by using a photon correlation technique [30P].

A review of low temperature measurement techniques and the status of Russian standards and codes relating to these measurements were reported [5P]. A general discussion described the selection stability and calibration of germanium thermometers in the 2–30 K temperature range [45P]. A magnetic thermometer is recommended for a checking standard for temperatures in this range [57P]. Two calibration procedures for platinum resistance thermometers were developed which result in calibrations accurate to within 0.01 and 0.025 K for the temperature range of 3.5–14 K and calibrations somewhat less accurate in the temperature range 2.5–3.5 K [47P]. A new bridge circuit used for measuring the thermal conductivity of solids at temperature below 30 K eliminates the influences of both sample temperature fluctuations and lead resistance [33P]. Significant field-induced temperature measurement errors were observed in a study of the low temperature behavior of carbon–glass thermometers in intense magnetic fields [62P]. The results of a parametric study of the aging phenomena in a low temperature glass–ceramic capacitance thermometer were found to be satisfactorily explained by an application of the Devonshire phenomenological theory of polar dielectrics [41P].

A new high temperature thermocouple pairing consisting of Ir-40Rh/Pt-40Rh has a nearly linear output with temperature, is more oxidation resistant than an Ir-40Rh/Ir pairing, has more than double the output of a Pt-40Rh/Pt-20Rh pairing and can operate at a higher temperature than a Pt-13Rh/Pt pairing [28P]. A measurement circuit was proposed which improved the accuracy of measuring temperatures in the 500–1300°C range using Pt–PtRh thermocouples [53P]. A double probe uses capacitive discharge to obtain the entire $I$–$V$ curve for energetic plasma beam experiments so that the electron temperature and ion density can be easily determined [43P].

A comparison of six common methods of converting thermocouple EMF values to temperatures indicated that two of the methods result in considerably larger errors than the other four [10P]. The transient EMF output of a fine wire thermocouple after an initial heating in static gas was found to decay exponentially, thus confirming the transient behavior can be characterized by a time constant [31P]. Reasonable predictions of the temperature response of an intrinsic thermocouple can be achieved using both finite difference and Runge–Kutta methods [25P]. Errors in the measurement of turbulent boundary-layer temperature profiles can be kept within acceptable limits by proper selection of thermocouple wire and proper probe design [13P]. A spectral remote sensing method appears to have potential for obtaining temperature distributions in semi-transparent materials at high temperatures where the data cannot be obtained using probes or radiation thermometry [67P]. Typical one-dimensional heat-transfer assumptions used when employing phase change coating measurement techniques may lead to large errors in the evaluation of local heat-transfer coefficients [55P]. Qualitative and quantitative heat transfer and fluid flow information can be obtained by employing cholesteric liquid crystals as a temperature sensing agent [16P].

A study of a laminated pyranometer indicated that it had a substantial non-uniformity of sensitivity and demonstrated the effect of the density and location of the thermocouple junctions on the output uniformity [50P]. Results obtained from an analytical model for the transient response of radiant heat flux gages agreed well with the measured responses of several gages to a step change of flux [37P]. The design and dynamic characteristics of two-sided thermal radiometers were described in [26P] and [27P].

Heat-transfer coefficients obtained from a thin-film naphthalene mass-transfer analogue technique for flow through a tube agreed with those given by the Colburn equation to within $\pm 5\%$ over a Reynolds number range $7.6 \times 10^4 < Re < 1.3 \times 10^6$ [49P].

Considerable effort continues to be expended in the design and development of apparatus for measuring the thermodynamic properties of substances. A high-pressure phase–equilibrium apparatus has a wide field of application in the study of reactions, densities, vapor pressures, liquid–vapor equilibria, and liquid–liquid equilibria [59P]. Using a "contact" type effusivity apparatus and an improved data reduction method, several properties of insulators can be determined [7P]. A technique to minimize difficulties in collecting vapor–liquid equilibrium data has been proposed which substitutes measuring phase densities for sampling [32P]. A device operating as a calorimeter with directional heat transport was developed to simultaneously measure thermal conductivity, enthalpy, specific heat, and thermal diffusivity of labile products [24P].

A new method of determining thermal conductivities of metals and semiconductors at high temperatures has been proposed [35P]. A coaxial cylindrical cell was used to measure the specific heats and thermal conductivities of a series of non-Newtonian aqueous solutions [9P]. A method was described in which the application of instrumentation used to measure thermal conductivity can be extended to simultaneously measure both the thermal conductivity and the thermal diffusivity of particulates [68P].

The specific heat of small (1–100 mg) samples can be accurately measured in the 1–35 K temperature range with an automated calorimetry system [54P]. The specific heat of both radioactive and nonradioactive samples can be measured in the temperature range of 2–60 K by using a heat-pulse technique [64P]. A method of measuring the thermal capacity of solid substances in the temperature range of 4.2–273.15 K was discussed along with a comparison of the results obtained for benzoic acid using the proposed method to results obtained by other investigators [52P].

The density of liquid $SF_6$ was measured at pressures up to 170 bar with a newly developed density float in order to demonstrate its applicability for high pressure density measurements [38P]. A method has been developed to obtain the latent heat of vaporization and specific densities of liquids by applying the Clausius–Clapeyron equation and determining the saturation densities from dielectric data and the Clausius–Massotti relationship [44P]. A new vibrating wire viscometer is particularly suited to studying a fluids viscosity in the critical region [15P]. The steady state heat-transfer rates from a heated tungsten wire in vacuum and in helium can be used to determine the resistivity, tensile breaking stress, and total hemispherical emittance of the wire and the thermal conductivity of the helium [36P].

Optical measurements on thin films, high temperature properties of opaque and transparent materials and various forms of differential measurements with as many as three reflecting samples are some of the possible applications of the instrument described in [19P]. A simple conversion of a grating monocrometer to a double beam instrument permitted optical absorption measurements to be made for various conditions [66P].

English-language translations of Russian papers dealing with the following topics appeared in *Measurement Techniques*: (a) calibration and characteristics of film thermocouples [34P]; (b) precision measurements of the temperature of a black body [39P]; (c) differential IR pyrometry of surface-heating nonuniformity [40P]; (d) calibration of a thin-film liquid-crystal heat detector [29P]; (e) an interference dilatometer for the temperature range of 293–1373 K [2P]; (f) a standard quartz dilatometer for the temperature range 20–30 K [61P]; and (g) a transducer for measuring the flow of a two-component liquid [4P].

## HEAT-TRANSFER APPLICATIONS

### *Heat exchangers and heat pipes*

An approximate explicit equation with empirical coefficients [15Q] describes the mean temperature difference for nine types of heat exchangers with counter current and cross flow arrangements. A calculation procedure [5Q] has been developed for the design of spiral heat exchangers. The wall temperature distributions have been calculated [13Q] for concentric pipe heat exchangers with laminar flow through the inner tube and turbulent flow through the annulus for spiral or countercurrent. A method of modeling the heat-transfer process is used for a parametric study [3Q] of heat exchangers with concentric tubes. An asymptotic solution [14Q] allows quick engineering estimates on enhancement of heat transfer by direct contact. Empirical correlations for heat transfer and friction are presented [21Q] for rectangular offset-fin plate-fin heat exchangers of varying geometry. A correlation equation including longitudinal heat conduction in periodic flow heat exchangers [16Q] agrees with a numerical analysis within ±0.5% for the operating range encountered in gas turbine applications.

A modified single-blow technique [10Q] measures the performance of heat-transfer surfaces well for any NTU value. Experimental results have been reported for a number of heat exchanger surfaces: for finned surfaces [23Q], for tube banks with straight or profiled longitudinal fins [11Q], for wire fins arranged in spirals [7Q], for oval tubes with transverse slatted fins [24Q], for plate finned surfaces [2Q], and for vertical spiral heat exchangers with turbulent counterflow of liquids [4Q]. Perforation of heat exchanger surfaces can result in a significant improvement of the heat-transfer and friction-loss performance [9Q].

Fine particles (of order 5 μm) were found [19Q] most effective in increasing heat transfer from dust-laden gases flowing along smooth tube bundles. Spray cooling of air-cooled compact heat exchangers improves heat transfer essentially with no change in friction when a liquid or condensing vapor is the medium to which heat is transferred [22Q]. Heat transfer was studied [20Q] in a scraper cooler with partial phase change. A turbine agitator was found [6Q] to be most advantageous in increasing heat transfer at the walls and bottom of an agitated cylindrical vessel. The results of this study are presented as dimensionless equations.

A review [12Q] of progress in heat pipe and porous heat exchanger technology includes enhancement by twisted tapes and by electric, magnetic, and ultrasonic fields. Fundamentals of heat pipe theory and design have been presented [8Q]. A theory [18Q] describing the thermal performance characteristics of single component and gas loaded heat pipes agrees well with experiments conducted with water and acetone. A theoretical and experimental investigation [17Q] determined optimum filling for heat pipes. An analysis of the performance of a heat pipe which pumps fluid along the tapered rotating wall agrees with experiments for Arcton 113 and 21 but not for water [1Q].

### *Aircraft and space vehicles*

Studies of ablation and heat shield performance still seem to be of interest although there is a decline of publication activity in this field. In connection with the design of heat shields for the base of re-entry vehicles, a computer model has been developed for describing teflon ablation. The model predicts both mass loss and temperature variations during and following aerothermic heating [8R]. The ablative performance of re-entry vehicle nosetips has been studied using ceramic heat shields. Discrepancies between predictions based on equilibrium thermochemistry and actual test data are discussed [13R]. Ablation studies of a large variety of graphitic materials in an arc-heated airstream at a surface pressure of 4.3 atm and a nominal surface temperature of 3925 K show that a wide variation in constituents, processing, fabrication, and structure have little effect on the ablation performance under the chosen test conditions [7R]. Results of ablation studies of graphite in high speed air streams suggest that carbon species other than $C_3$ do not influence ablation results to any large degree [10R].

The thermal protection for a space shuttle vehicle requires improved oxidation resistance of the leading edge. Tests revealed a superior performance of silicon-bearing resin which provides higher strength and at least 100% better oxidation resistance compared with other composites [12R]. Using camphor and wax as low temperature ablation materials which sublimate and liquefy, respectively, at the chosen test conditions (free stream Mach number of 5.3), the cross-hatching phenomenon has been studied indicating that the existence of a transitional or turbulent boundary layer is a prerequisite for the appearance of this pattern and the viscosity of the solid ablation material influences the streamwise spacing of this pattern [11R]. Base re-entry vehicle heat-transfer measurements at $M$, = 18 reveal clearly the influence of both the radial gradient and the local cone flow field on turbulent base heat transfer [1R].

Estimates of non-equilibrium radiation for Venus entry show that the radiative heating rate is approximately twice the corresponding equilibrium value at peak heating [6R]. Investigations of aerodynamic heating on 3-D bodies in hypersonic flows demonstrate that the effects of entropy layer swallowing on the calculated heating rates are small for laminar heating but large increases occur for turbulent heating [3R].

Heat-transfer measurements in hypersonic particle erosion environments show heating levels far in excess of clear air values. The primary heating augmentation mechanism is due to convective heating caused by particle distortions of the aerodynamic flow field [4R]. Spectrometric measurements of the exhaust jet of a rocket indicate that temperature relaxation between carbon particles in the center of the jet and the surrounding gas is a relatively slow process [9R].

Rapid graphical methods are described for estimating the minimum internal insulation requirements for liquid-fueled ramjets with superalloy motor cases cruising at Mach numbers between 3 and 5 at altitudes between 13000 and 30000 m [5R].

The burning rate of a double base solid propellant (nitrocellulose and metriol trinitrate) may be increased from 0.2 to 0.6 cm/s by exposing the propellant to the thermal radiation of a xenon arc [2R].

*General*

A computer calculation [9S] of local flow properties in four two-dimensional furnaces is based on a two-equation turbulent model and either on instant reaction or on the Arrhenius model for the chemical reactions involved. The results compare well with experimental ones. The distribution of temperature and heat flux in the combustion chamber of a steam generator burning oil and employing gas recirculation has also been investigated [13S]. Several papers [11S, 12S, 20S] analyze the stratification of the flow through steam generating loops due to thermal nonuniformity. Measurements of mass transfer and erosion of metals by combustion gases [14S, 17S] established various erosion regimes.

Experimental results [21S] describe the critical heat transfer in tubular fuel elements of nuclear power reactors. Hot spots arise in the fuel cladding of liquid metal reactors due to deposition of fuel debris or to fission gas impingement. They were studied [8S] analytically and experimentally.

Temperature distributions at the outlet of a gas turbine combustor with a mixer were investigated [2S]. Measurements in a cascade with rotor blades established [5S] the effect of Mach number and temperature factor on heat transfer to the turbine blades. Experiments on stationary turbine blades were used [6S] to improve the reliability of existing prediction methods by the inclusion of the effect of turbulence in the freestream. Dimensionless correlations were developed [15S] to describe unsteady heat transfer in turbine inlet valves during startup. Models were developed [1S] to describe heat transfer connected with axial flow in rotary combustion engines.

An analogy [10S] between heat and mass transfer at the wall of a stirred tank includes the influence of Prandtl and Schmidt numbers. The unsteady cooling of the surrounding rock during the advance of a mine was analyzed [18S]. The results are found tabulated. A model for the analysis [19S] of heat transfer in the spray of mechanical atomisers agrees satisfactorily with experimental results.

Analyses and experiments [3S] considered the heat transfer to moving fibers. Microwave [7S] and laser radiation [16S] induced temperature increases in rabbit eyes which were used to develop an analysis useful in cataract research. Heat transfer from a blood vessel through the skin surface to a cooled strip is optimized [4S] when the strip width equals three times the distance to the vessel. The heat extracted, however, was found to be small (0.9 W/mC).

*Solar energy*

Solar energy studies continue to increase as the need for alternative energy sources becomes more apparent and as the level of governmental research and development funds increases. The interest in the field is reflected by the increase in heat-transfer related solar energy papers. Topics of major interest among these papers include solar insolation, collectors, thermal storage, and systems studies.

Good estimates of five-day mean values of global solar radiation can be made based solely on the values of precipitable water and observations of the type and amount of clouds for different layers in the atmosphere [2T]. Approximate methods were presented to estimate the coefficients which are required to use the equations suggested by ASHRAE for the calculation of direct and diffuse solar insolation [22T].

In the 1975 November issue of the *ASHRAE Journal*, there are survey articles dealing with flat plate collectors [3T], and thermal energy storage [14T]. The problem of designing solar energy collectors for delivery of heat at minimum cost was investigated [12T].

A simple closed-form expression facilitates the accurate estimation of the infrared emittance and solar absorptance of a flat plate collector having a honeycomb absorber [26T]. A modification of previous equations and data resulted in a general relation for the instantaneous rate of energy transferred by radiation and convection to a transparent cover above an absorber plate [10T]. A collector with two covers and a highly absorbant "black" liquid, which flows in transparent channels and directly absorbs solar energy, was found to be nearly equivalent in collection efficiency to a collector with two covers and a black (non-selective) coated metal absorber plate [18T].

A number of approaches have been evaluated for increasing the collection efficiency of flat plate collectors. It has been predicted that a combination of evacuating a flat plate collector to a pressure of 1–25 torr to eliminate internal convection heat transfer and applying a selective coating to the absorber plate can increase the daily energy collection as much as 278% over that obtained with a non-evacuated collector having a non-selective absorber coating [5T]. The performance of flat plate collectors can be significantly enhanced by the use of flat reflectors to increase the total collection area, particularly if the reflectors are specular, are in a south-facing geometry, and are used with collectors elongated in the east–west direction [24T]. Another evaluation of the effects of enhancing a flat plate collector with a reflective surface predicted that optimum orientation existed when the collector plane was nearly perpendicular to the plane of the reflector and further predicted that the optimum reflector angle for winter conditions was between 0° and 10° above the horizon [15T].

Concentrating solar collectors have also been studied. A general prescription for designing a cylindrical mirror to concentrate radiation onto a tube of general shape was developed which resulted in achieving the maximum concentration ratio [27T]. Another analysis developed a differential equation for the shape of a reflecting surface which will convert a collimated beam of light of any intensity distribution into another specified distribution over an arbitrary surface [1T]. A solar collector having a fixed spherical mirror and a sun-tracking cylinder absorber was predicted to be capable of collecting approximately 60% of the direct-normal solar flux incident on the mirror when operating with absorber temperatures greater than 600 K [13T]. The use of a linear Fresnel lens as a seasonally-adjusted concentrator resulted in a collector design which had a daily collection efficiency (with no thermal losses) of approximately 50% and a concentration ratio of approximately 5 [19T].

Materials with spectrally selective radiation properties are useful in both flat plate and concentrating solar collectors. An increase in the transmission of the cover plates of a flat plate solar collector either by using low-iron glass to minimize cover plate absorption or by using a coating to minimize cover plate reflection was predicted to increase the collection efficiency by up to 44% as compared with the use of conventional soda-lime glass [6T]. The preparation and durability of an etched anti-reflection coating for glass, a vacuum deposited selective absorber coating for high temperature (400°C) absorbers, and an electroplated selective absorber coating for lower temperature (200°C) absorbers have been demonstrated [20T]. A black-chrome selective solar absorber coating has been developed which has an estimated solar absorptance of 0.87 and an estimated emittance of 0.09 at a temperature of 120°C [16T].

The thermal interaction between an underground heat storage system and the surrounding ground was studied [25T]. Eutectic fluoride mixtures of alkali and alkaline earth metals in combination with a multi-layer insulation system lead to a reduction of the volume and weight of a storage unit by a factor of three as compared to other storage units such as batteries and super flywheels [23T].

A system simulation program for solar assisted heating and cooling systems has been developed and its use was illustrated for a number of operating conditions of a solar assisted heating system [11T]. The problem of determining the optimum tilt angle for a flat plate solar collector was investigated as a function of latitude, weather data, and energy demand characteristics [9T]. A model for frost formation based on molecular diffusion of water vapor at the frost surface and using energy and mass balances permit frost thicknesses to be predicted within 30% for conditions which include time varying environmental parameters [8T].

The largest solar assisted heating and cooling system designed to date will be used to condition an elementary school in Atlanta, Georgia and the collectors are expected to provide 60–100% of the energy needs to cool the building [4T].

Studies of power generation from tides, ocean thermal gradients, and geothermal wells have also been reported. Based on a review of recent U.S. funding of the research and development of renewable energy sources, and a study of the technical and environmental acceptability status of tidal, wind, and sea thermal power generation systems, it was found that tidal power generation is presently technically feasible but economically uninviting [7T]. Preliminary results from an optimization program for heat exchangers for ocean thermal power plants verified previous studies which showed the sensitivity of the heat exchanger design to the cold water pumping tube size [17T]. The discharge temperature of the water from 28 geothermal wells was predicted with a mean absolute error of 1.5°C and a maximum error of 4°C [21T].

## PLASMA HEAT TRANSFER

Heat-transfer studies in plasmas and MHD channels refer to fundamental investigations as well as to applications, in particular to those using electric arcs as heat source.

Arc constriction in lamps containing mercury and iodine at pressures of several atmospheres is mainly due to molecular radiation losses from the plasma at temperatures between 2500 and 4500 K [5U]. Radiation losses in the anode constriction region of atmospheric pressure high intensity argon arcs diminish temperature peaks causing a slight increase of the arc diameter [15U]. Severe artificial constriction of an arc in front of the anode may result in current densities $\geq 10^5\,\mathrm{A/cm^2}$ and corresponding power densities of $4.5 \times 10^6\,\mathrm{W/cm^3}$. This type of "point arc" is considered as a heat source for welding, cutting, etc. [2U].

A numerical analysis of a 60 Hz atmospheric pressure argon arc located in a constant diameter channel attached to a converging nozzle indicates that near the arc core radial convection, radiation, and axial convection processes are dominating whereas in the arc fringes radial conduction is the main heat transfer mechanism [6U]. In plasma-arc welding, heat transfer by convection is an important process by which 27–31% of the total power input to the arc is transferred to the workpiece. Radiation may account for 17–19% [13U]. For arcs burning to an upstream cathode of sintered copper/tungsten in an $M = 0.8$ air flow, radiation is the dominant energy transfer mechanism, accounting for more than 50% of the power dissipation in the arc column. The presence of upstream electrode vapor in the arc column is responsible for the high radiation losses [16U]. For high pressure ($50 \leq p \leq 500$ torr) sodium arcs of 7.6 mm dia and power inputs between 2.8 and 5.8 kW/m a good agreement is found between measured and calculated temperature distributions ($3600 \leq T_{\max} \leq 4100$ K) and the corresponding radiation in the visible range of the spectrum [4U].

Calculated composition, electrical conductivity and total radiation of an atmospheric pressure nitrogen plasma for temperatures up to 30 000 K are presented and compared with previous calculations [14U]. Static and dynamic properties of arcs near plane surfaces are strongly influenced by the cooling effect of the nearby wall. Agreement with theory is much better for dry surfaces, suggesting that humidity in the arc greatly affects the static and dynamic properties [12U]. A transverse magnetic field interacting with a constricted argon arc at 1 atm has a substantial effect on the arc performance. A dual vortex flow is induced which displaces the hot core toward the wall, giving rise to increased and non-uniform wall heat fluxes and enhanced field strengths [1U].

The current density and heat flux distribution around a cylindrical probe immersed into an atmospheric pressure argon plasma cross flow ($T = 13\,240$ K, $v = 230$ m/s) show a pronounced peak at the front stagnation point. In the boundary layer close to the front stagnation point frozen conditions prevail whereas the boundary layer near the rear stagnation point seems to be in chemical equilibrium [10U]. Modeling of a heterogeneous plasma jet reactor operated in argon or nitrogen atmosphere (5000–12 000 K) which is characterized by non-isothermal, turbulent, compressible, swirling, confined flow permits prediction of particle trajectories needed for heat-transfer calculations. The model has been applied for studying the decomposition of molybdenum disulfide particles into molybdenum metal and elemental sulfur [3U].

Iron oxides can be converted directly to a virtually pure molten iron in a single-step arc-plasma reactor process using hydrogen and natural gas as reductants [7U]. A survey on the use of radio frequency plasmas for chemical synthesis refers to the thermal decomposition of gases and liquids, reduction reactions, oxidation reactions, making of refractory compounds, nitrogen fixation, and plasma heat treatment of solids [8U].

A two-group radiation transport equation is derived for calculating radiation cooling of MHD exhaust gases in a steam generator [4U].

Studies of the combined influence of viscosity, Hall effect and ion slip on velocity and temperature fields as well as on heat transfer in an MHD channel show that the Nusselt number increases with increasing (modified) Hartmann number and decreases with increasing reduced Hall parameter [9U]. In MHD channels employing seeded combustion gas mixtures, the effect of radiation cooling on temperature and associated electrical conductivity distribution is significant for substantial values of the effective absorption coefficient [17U].

Overall heat-transfer measurements are reported both in laminar and in turbulent flow for combined forced and free convection in a vertical Hg–$H_2O$ heat exchanger under the influence of a transverse magnetic field. An increasing magnetic field first reduces the heat transfer in Hg by suppressing turbulent fluctuations and free convection. As the flow becomes laminar the Hartmann effect dominates leading to an increase of the heat transfer [18U].

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