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HEAT TRANSFER—A REVIEW OF 1980 LITERATURE

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INTRODUCTION

This review surveys results that have been published in the open literature covering various fields of heat transfer during 1980. As in the past, the number of papers published during that period was such that a selection only can be included.

The 19th National Heat Transfer Conference, sponsored by the American Institute of Chemical Engineers and the American Society of Mechanical Engineers, was held at Orlando, Florida, 27–30 July 1980. Thirty-five sessions were devoted to research in basic modes of heat transfer and to heat transfer applications in coal conversion, solar energy, laser systems, radioactive waste handling, fusion reactor components, gas turbines, LNG shipping and storage, and passive solar systems. Heat exchangers for two-phase applications, for high temperatures, and air cooling were also discussed. Courses in the AIChE-Today Series and in the ASME Professional Development Series provided the opportunity to become acquainted with new developments in various fields of heat transfer. Invited lectures were given by E. R. G. Eckert on "Pioneering Research," by E. H. Young on "History and Development of Application of Extended Surface Tubes," and by S. W. Churchill on "Adventures in Heat Transfer." D. K. Slayton of NASA discussed during the Awards Luncheon the development of the insulation protecting the space shuttle vehicles during reentry. The Max Jakob Memorial Award was presented to S. W. Churchill and the D. Q. Kern Award to E. H. Young. J. M. Robertson was the recipient of the Conference Award Certificate for the best paper on "boiling heat transfer with liquid nitrogen in brazed aluminum plate fin heat exchangers." The papers presented at the conference are available as preprints or in the publication series of the American Institute of Chemical Engineers. Many will also be published in the Journal of Heat Transfer.

The 101st Winter Annual Meeting of the ASME provided lectures and discussions on heat transfer in 19 sessions or symposia. Application areas like frost and ice formation, arctic heat transfer, OTEC systems, MHD and fusion reactors, and nuclear waste disposal were covered. S. P. Kezios, the luncheon speaker, discussed "Perspectives in Heat Transfer—Highlights in the Development of ASME Heat Transfer Division." J. H. Lienhard received the Heat Transfer Memorial Award. The papers presented at the conference are available as preprints or in book form at ASME Headquarters. Many of them will also be published in the *Journal of Heat Transfer*.

The 27th Heat Transfer and Fluid Mechanics Institute was held during 23–25 June 1980 at the University of California. Proceedings of the conference, which presented several papers on heat transfer, are available through the University of Southern California.

The Annual Winter Meeting of the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) was held on 3–7 February 1980 in Los Angeles and the ASHRAE Annual Meeting on 22–26 June 1980 at Denver, Colorado. Many of the papers presented dealt with heat transfer problems. They are available as preprints or in the conference proceedings through ASHRAE Headquarters.

The Sixth National Heat and Mass Transfer Conference in the USSR was held at Minsk, 11–13 September 1980. Information on the proceedings of the conference can be obtained at the Luikov Heat and Mass Transfer Institute, Minsk, USSR.

A joint U.S./Japan Heat Transfer Seminar was held 29 September–2 October 1980 in Tokyo, Japan sponsored by the Japan Society for the Promotion of Science and the National Science Foundation. Thirteen U.S. delegates attended and about twice that number of Japanese delegates. T. Mizushina and W. Aung discussed the present status of heat transfer research in Japan and in the United States, respectively. The subsequent papers dealt with basic heat transfer phenomena, and with applications like heat storage, heat recovery, and non-conventional energy.

Three sessions on heat transfer were included in the program of the 25th Annual International Gas Turbine Conference of the Gas Turbine Division of the ASME. The keynote paper was presented by R. W. Graham on the subject "The Impact of New Instrumentation on Advanced Turbine Research." Papers are again available either as preprints or in book form at ASME Headquarters.

A number of books dealing with heat transfer or including heat transfer topics have appeared on the market. They are listed in the bibliographic portion of this review.

The following highlights illuminate developments in heat transfer research during 1980.

The heat conduction literature was dominated by problems involving change of phase. There was considerable activity in the development of numerical solution methods, and analytical solution methods were also formulated.

Once again this year, heat transfer in channel flows continued to be an area of active experimental and theoretical research. Flows in channels of different geometries and/or flows of non-Newtonian fluids were an area of great interest. Many authors addressed ways to enhance heat transfer by internal finning, roughened walls, and various turbulence promoters. Finally, the problems of the coupled effects of the various heat transfer modes—natural and forced convection or convection and radiation were addressed.

The literature contains numerical and experimental investigations of wall boundary layers. Attention is also given to cylinders in cross flow, stagnation point, free jets, and impinging jets.

Heat transfer in flow with separated regions on single or multiple objects, in cavities or ducts were studied. Impinging jets found attention as a means to increase heat transfer. Considerable efforts were directed to studies of heat transfer in porous media in two or three component systems without or with phase change and with the solid as packed bed or in the fluidized state.

Papers on transfer processes dealt with measurements of turbulent fluctuations, diffusion and thermal diffusion mechanisms, transfer processes in fluidized beds, and moisture transport in soils.

Natural convection research continues to be of expanding interest among heat transfer researchers. A large portion of the papers published this year addressed the problems of combined heat and mass transfer adjacent to inclined plates or cylinders. Various flow conditions ranging from laminar steady flow to turbulent transient convection flows were studied for fluids of constant or variable properties. The following other subjects were also examined with respect to natural convection: thermal instability, periodic vortex formation and staggered and continuous plate arrays.

Analysis and mass transfer experiments increased our knowledge of heat transfer in various rotating systems.

Heat transfer with change of phase remains an active area of research and continues to be one where there is much yet to be learned. Boiling heat transfer literature is divided between papers dealing with fundamentals and papers on practical applications for specific geometries, fluids, or surface materials. Many of the "applications" papers deal with reactor heat transfer. Boiling of cryogenic fluids, boiling on structural surfaces, and dry patch formation and rewetting were discussed frequently. Evaporation of liquid films and condensation on liquid films covering horizontal tubes appear to be areas of increasing interest. Condensation of flow forced through porous media, with applications to secondary oil recovery, was an area of interest which promises to increase in popularity.

Radiation transport in emitting, absorbing, and scattering media is of increasing interest.

Laser–Doppler anemometry techniques continue to be developed for a large variety of heat transfer situations. A substantial decrease occurred in the number of papers describing new hot-wire/hot-film anemometry methods. The number of papers dealing with temperature measurement techniques increased.

Optimization of heat exchangers by new heat transfer surfaces and proper dimensioning of the units in groups of heat exchange equipment was studied.

The number of papers on heat pipes decreased this year.

Solar energy utilization continues to be an active area. The largest number of papers dealt with the experimental and analytical evaluation of the performance of solar collectors. The number of papers dealing with thermal energy storage increased while those describing studies of the radiation properties of materials used in solar collectors diminished.

Plasma heat transfer studies are attracting increasing attention, especially those related to applications of electric arcs.

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

- Conduction, A
- Channel flow, B
- Boundary layer and external flows, C
- Flow with separated regions, D
- Transfer mechanisms, E
- Natural convection—internal flows, F
- Natural convection—external flows, FF
- Convection from rotating surfaces, G
- Combined heat and mass transfer, H
- Change of phase, J
- Radiation
  - Radiation in participating media, K
  - Surface radiation, L
- MHD, M
- Measurement techniques, P
- Heat transfer applications
  - Heat exchangers and heat pipes, Q
  - General, S
  - Solar energy, T
- Plasma heat transfer, U.

CONDUCTION

The conduction literature continues to be dominated by problems of phase change. Solution methodologies, both numerical and analytical, have evoked some interest, as have fins and composite materials.

Experiments on the melting of various paraffins in a vertical annulus affirmed the important role played by natural convection in the melt region [5A]. Interferometric observations added further insights into the role played by liquid-phase natural convection in the freezing of a liquid whose temperature is above the fusion temperature [49A]. In the convectively unstable situation of freezing from above, the convection may decrease the rate of solidification if the Rayleigh number is sufficiently large. For melting from below, natural convection develops rapidly and greatly influences the motion of the phase-change boundary [15A]. Heat transfer during melting at horizontal cylinders was studied experimentally for uniform surface temperature and uniform wall heat flux, for both *n*-heptadecane and *n*-octadecane as phase-change media [6A]. For the onset of surface tension-driven convection, the critical Marangoni number is always smaller for solidifying fluid layers than for those not undergoing a phase change [1A].

During experiments on the effects of turbulent flow on freezing in a tube, an unexpected oscillatory phenomenon was encountered [46A]. Solidification of molten metals flowing in pipes was studied both numerically and experimentally in response to the need for information about the castability of metals and alloys [23A]. The problem of freezing at the wall in a laminar pipe flow has been extended to include axial heat conduction, with solutions being obtained for values of Peclet number as low as unity [26A].

As it cools, the solidified part of an ingot contracts and creates a small gap between the ingot and its mold. Numerical solutions showed that the presence of the gap increases the time of complete solidification [7A]. An analysis of the solidification of metals in a mold takes account of a heat transfer coefficient at the metal—mold interface [10A]. A computer simulation has been performed of the heat transfer, mass transfer, and fluid flow during the growth of a single crystal [22A].

A modification of the heat balance integral enabled a solution to be obtained for inward freezing in cylindrical coordinates [48A]. Biot's variational method has been extended to a problem of melting due to radiative heating; it was assumed that the melt is removed immediately upon its formation [36A]. The fictitious-domain technique, used earlier for homogeneous, steady conduction, has been extended to the two-dimensional Stefan problem [20A]. The total melting time for simple bodies subject to convective boundary condition can be estimated by evaluating an algebraic equation, as can the melting time for a rectangular body with an imposed surface temperature [42A, 43A].

A model describing the heat transfer, solute redistribution, and interface stability during the planar solidification of an aqueous binary solution has been developed [32A]. A generalized solution for unidirectional planar freezing at constant temperature of a supercooled aqueous solution is valid for both dilute and non-dilute solutions and also at both short and long times [27A]. If, in the process of solidification, the liquid phase contains a gas phase in solution, the gas will be rejected at the phase interface due to the difference in solubility of the gas in the liquid and solid. Experiments to clarify the effects of the presence of the gas were performed for freezing of liquid water containing nitrogen gas [35A]. The solidification of a binary alloy has been solved via a series [45A].

Interest remains strong in numerical solution methods. A new algorithm is developed for the numerical solution of the multi-dimensional transient diffusion equation with an implicit formulation. This algorithm can be considered as a generalization of the tridiagonal algorithm commonly used for the one-dimensional transient diffusion problem [51A]. Specialized moving finite elements have been developed that can be employed to generate a nonlinear heat conduction model for situations involving traveling boundary and heat generation fields superposed on an initial state. To facilitate the solution of the resulting nonlinear finite-element formulation, a multilevel heuristic iterative solution strategy is developed [33A]. In a study of the use of finite elements for transient conduction—forced convection problems, the advantages and disadvantages of conventional versus upwind convective finite elements were evaluated [47A]. A grid refinement method was proposed for the finite element solution of transient temperature fields which result from a sudden change in the temperature of a fluid in contact with the boundary of a solid [34A]. For the solution of the Poisson equation by the finite element method, the use of a weighting function corresponding to the control volume method gave more accurate results than did a weighting corresponding to the Galerkin method [37A]. Long-time solutions to heat conduction transients with time-dependent inputs have been obtained by a method which begins with either a finite-difference or finite-element model of the heat transfer problem and produces response coefficients [8A]. A transport equation approximation to the heat conduction equation served as the basis of a new Monte Carlo approach for solving heat conduction problems [12A].

Fins continue to draw some attention. New parameters, the thermal transmission matrices or ratios, have been proposed to replace the efficiency as a performance measure of fins [24A]. The effects of temperature-dependent thermal conductivity and position-dependent heat transfer coefficient were taken into account in solutions aimed at obtaining optimal dimensions of circular fins of trapezoidal profile [38A]. The method of transformed groups was used to avoid the iterative procedure that is commonly used to integrate the nonlinear fin equation [24A]. In an analysis of steady periodic heat transfer in convecting fins of arbitrary profile, both the cases of periodic variation of the base temperature and periodic variation of the environment temperature are considered [3A]. Two-dimensional numerical solutions of a rectangular fin and its related base surface wall were compared with one-dimensional solutions, and the conditions were identified when the one-dimensional results either exceeded or fell below the two-dimensional results [16A].

Composites and layered material are treated in several papers. Green's functions were used to solve the transient heat-conduction problem for a two-layer composite consisting of a core of one material and an envelope annular ring of a second material [39A]. They were also used to obtain analytical solutions for heat conduction in composites of infinite, semi-infinite, and finite laminates in the unsteady, periodic, and steady modes [18A]. In models that were formulated to determine the influence of bonding materials on the heat diffusion in otherwise bi-laminated composites, the geometric arrangement of the composite with the bond was treated as a special type of tri-laminated composite in which each of its major constituents is sandwiched between two bonding layers [31A]. It was shown that two bodies that are pressed together and exchange heat by conduction may not necessarily remain in full contact and can separate locally if heat flows into the material with larger distortivity [11A].

Miscellaneous heat conduction solutions continue to appear. A problem of conjugate heat transfer was solved in which transient conduction in a wall interacted with boundary layer convective heat transfer from one face of the wall [9A]. The thermal stratification of a stagnant lake or tank, subject to surface heating, was solved as a problem of transient heat conduction, with convection and eddy viscosity being neglected [14A]. Charts have been prepared which give the surface temperature oscillations of electrical resistance heaters supplied with alternating current [19A]. In a problem of steady conduction in a rectangle, one of the surfaces was convectively coupled to an isothermal environment while the opposite surface was subjected to a non-zero flux distribution over part of its length. The problem was solved by standard separation of variables [40A].

For the inverse problem of transient heat conduction, an analytical solution was obtained for the case in which the given temperature information is periodic in time [13A]. In a variant of the inverse problem of transient heat conduction, a method is presented by which scanned surface temperature data from a body are used to predict the cavity lying beneath the surface [17A].

Analytical solution methods continue to be evolved. Approximate closed-form solutions to three-dimensional steady conduction problems can be obtained by a method borrowed from elasticity problems [4A]. A boundary-fitted coordinate system which transforms a region onto a fixed rectangular domain was employed as the basis for solving two-dimensional, steady, anistropic heat conduction problems [28A]. The use of a helical coordinate system was shown to be advantageous in solving for the steady temperature distribution in a heat-generating helical coil [50A]. A general steady state solution, obtained by the finite integral transform technique, contains one less infinite series than is encountered when all partial derivatives with respect to the space variables are removed from the differential equation by integral transformation [29A].

Theoretical and mathematical issues were addressed by several authors. In a mathematically oriented study of the nonlinear Fourier equation, it was shown how positive majorants and positive minorants can be used to furnish upper and lower bounds which govern the intensity of the heat generation in a certain exothermic process [30A]. Mathematical issues have been dealt with for a rigid heat conductor with memory [41A]. Second law considerations led to Lagrangian and Hamiltonian formulations of heat conduction [21A]. A thermodynamic approach to rigid heat conductors introduces the heat flux vector as independent variable while its temporal evolution is governed by a first order differential equation. The form of the second law is that wherein the entropy flux and the entropy source are not given *a priori* but are determined through constitutive equations [25A]. For a particular form of the hyperbolic heat equation, it was found that the velocity of a temperature wave in a simple medium depends inversely upon the temperature to the three-quarters power [44A].

CHANNEL FLOW

The study of heat transfer in channel flow configurations was an area of very active research. Experimental results were presented for turbulent heat transfer in large aspect channels. The results were compared to both theoretical and empirical results [25B]. Velocity and temperature profiles were computed for developing turbulent flow in a square duct with constant wall temperature, constant wall heat flux or asymmetric heating. The computations utilized an explicit numerical differencing scheme and an algebraic closure model based upon a three-dimensional mixing length, and the results were in good agreement with measured data [15B]. A numerical study of heat transfer in a 90°, constant cross-section curved duct, steady, laminar flow was presented which was aimed primarily at characterizing the effects on heat transfer of duct geometry and entrance conditions during the developing period of the flow. Calculations were based on fully elliptic forms of the transport equations and a comparison of results based on parabolic equations showed how the latter approach can lead to erroneous results for strongly curved flows [83B]. Experiments were performed to determine entrance-region and fully developed heat transfer characteristics for turbulent air flow in an unsymmetrically heated equilateral triangular duct; friction factors were also measured. The fully developed *Nu* numbers based upon hydraulic diameter did not compare favorably with circular tube correlations. However, excellent *Nu* number predictions were obtained by employing the Petukhov–Popov correlation in conjunction with the measured friction factor for the triangular duct [2B]. Naphthalene sublimation was used to measure the local and average heat transfer coefficients on the downstream face of an enlargement step in a pipe. The highest values of the local transfer coefficient were found to occur on the portion of the enlargement face adjacent to the aperture through which the flow enters the enlarged space. The lowest coefficients occur in the corner where the enlargement face meets the wall of the enlarged pipe [74B]. Naphthalene sublimation was used to study the heat transfer and pressure drop characteristics of an array of staggered plates aligned parallel to the direction of a forced convection air flow. For a given operating condition, the per-plate heat transfer coefficients were found to be the same for the second and all subsequent rows. The fully developed heat transfer coefficients increase with Reynolds number for all of the plate thicknesses investigated and, in general, thicker plates give rise to higher heat transfer coefficients [72B]. An analytical study was made of the laminar flow and heat transfer in ducts whose cross-section is bounded by a wall with periodic corrugations distributed across the span; the other bounding wall is parallel to the corrugated wall and is plane. The results determined numerically demonstrated that if the temperature of the duct wall is to be minimized, a corrugated duct can be highly effective but at the price of additional surface area and greater duct height [67B]. A finite difference formulation was used to analyze laminar fully developed flow and heat transfer for a duct in which there are cross-sectional non-uniformities, e.g. a spanwise periodic array of rectangular protuberances from one wall. The protuberances affected the convective heat transfer by both altering the velocity field and by serving as fins [69B]. Both mixing-related hydrodynamic processes and the effects of the thermal imbalance of the component air streams were studied in a tube downstream of a tee in which air streams of different temperature are mixed [70B]. Complementary heat transfer and fluid flow experiments were performed to determine transfer coefficients and pressure drops associated with the pressure of a slat-like blockage in a tube. The flow was turbulent in all cases, and the heat transfer coefficients in the region just downstream of the blockage were found to be several times as large as those for a corresponding conventional turbulent pipe flow [73B].

Analytical and experimental results were presented for a fully developed turbulent flow in a curved channel with a rectangular cross-section under the condition of a constant wall heat flux. A secondary flow appears in the channel due to centrifugal force, and the flow and temperature fields are strongly influenced. The coefficient of resistance and the Nusselt number were obtained analytically and experimentally for air, and were in good agreement with previous results [38B]. Regular perturbation techniques were employed to investigate the nature of the known equations governing fully developed forced and free convective flow between heated parallel walls. Particular attention was given to the solution near the critical Rayleigh numbers, at which infinite flow rates are predicted by linear theory; and some tentative suggestions were presented on the transitional mechanisms between the various flow regimes [6B]. Measurements of pipes and channels with non-circular cross-section were performed for laminar flow operating conditions [62B]. The problem of turbulent heat transfer in a revolving square-sectioned tube was studied [49B]. The onset of significant departure from isothermalities caused by viscous energy dissipation in flow through a slit was determined for isothermal and adiabatic walls. A series solution of the energy equation enabled calculation of dimensionless profiles for any power law fluid, and such solution provides useful standards for judging the performances of numerical schemes for solving complex non-isothermal flows [82B].

Experimental information was presented for single phase forced convection in a circular tube containing a two-dimensional rib roughness which examines the effect of the rib helix angle. Heat transfer and friction characteristics for air flow were reported for three helix angles (30, 49 and 70°). It was concluded that the preferred helix angle is 45° [19B]. Experimental investigations were performed to improve the concepts of the influence of mass velocity, enthalpy of the flow, and height and and pitch of the fins on the conditions leading to burnout in tubes with internal helical finning [39B]. A numerical analysis was presented for fully developed laminar convective heat transfer in tubes with internal longitudinal fins and uniform outside wall temperature. The distributions of fin temperature, fluid temperature, and local heat flux were shown to be strongly dependent upon the finned tube geometry and in some cases on the fin conductance parameter as well [66B]. A parametric analysis of the performance of internally finned tubes in turbulent forced convection was presented for application to heat exchangers. The best axial internal fins offer less than 10% material savings for equal pumping power; however, material savings are increased to 49 percent using internal fins having a 30° helix angle [79B]. The experimental data on heat transfer in tubes with twisted tape turbulence promotors was correlated in a manner which accounted for the actual pattern of the fluid flow in the spiral channel. It was concluded that sufficient accuracy can be obtained by using the well known equations for laminar and turbulent axial flow in a cylindrical channel [52B]. Experiments to assess the effectiveness of turbulence promoters in tubes with non-uniformly heated perimeters compared the temperature conditions of a smooth tube and tubes with twisted tapes at the same test parameters. The results showed that under conditions of "normal" turbulent heat transfer, the effectiveness of the twisted tape is comparatively low. In contrast, under conditions of impaired heat transfer, there is a high effectiveness attributed to the laminarization of the flow in the smooth tube [31B]. A numerical analysis carried out for laminar heat transfer in a circular tube subjected to an axially periodic variation of the external heat transfer coefficient found that external finning yields substantial heat transfer enhancement compared with unfinned tubes [68B]. Using a parallel plate duct in which one surface was heated and the other surface was insulated, experiments were carried out to examine the effects of a single roughness element on the insulated wall on the heat transfer of the opposite wall. For a variety of roughness elements and over a range of Reynolds numbers, local heat transfer coefficients, the velocity distribution, and the turbulence intensity after the roughness and drag coefficients by the single roughness element were measured. The local heat transfer coefficient distribution along the flow direction after the roughness element shows two or three peaking values, and these peaks seem to be explained by examining the velocity distribution and the turbulence intensity along the flow direction [23B]. Experimental data on hydraulic resistance and heat transfer in a stream of water passing through an electrically heated circular tube fitted on the inside with spiral vortexing bands of various pitches were presented. The results correlated with previously published dimensionless relationships within accuracy of 3–5% [13B]. Experiments on fully developed turbulent flow in a rectangular channel with various aspect ratio were performed to determine the parameters of the velocity profiles over two-dimensional rectangular roughnesses. Results showed that the slopes of the non-dimensional velocity profiles in the smooth and rough zones decrease with increasing relative roughness, height, and drag of the rough wall [46B].

A study was made of the average rate of heat transferred to the wall of a rectangular channel when a hot incompressible non-Newtonian fluid flowed through it. The results showed an increase in the heat transfer coefficient for those fluids which exhibit large strain-rate gradients in the wall region of an arbitrarily rectangular channel [14B]. An experimental study of laminar heat transfer to in-tube flow of non-Newtonian fluids provided results for the Nusselt number which were compared with numerical predictions and experimental data. Two correlations were recommended according to the temperature dependence of the rheological characteristics [30B]. Velocity profiles exhibiting maxima away from the axis of symmetry were calculated for supercritical carbon dioxide flowing vertically in a heated circular duct. The analysis was carried out at the two-dimensional level and the turbulent fluxes were represented by a two-equation model of turbulence [24B]. A calculation procedure was presented for flow and heat transfer in ducts of annular cross-section which was applied to both laminar and turbulent flows. The procedure was used to study heat transfer in the laminar flow of water and ethylene glycol in vertical ducts which predicted the onset of the flow reversal caused by the effect of buoyancy when only one wall is heated [45B]. A study of the heat transfer characteristics to a non-Newtonian flow between parallel plates was performed which accounted for variable fluid properties [42B]. The problem of laminar heat transfer in circular tubes to power law fluids with temperature dependent rheological properties was solved numerically including the effects of viscous dissipation but neglecting internal heat generation. A finite difference scheme applied for the boundary condition of constant wall temperature provided results in good agreement with those previously published [21B]. Numerical computations of the pressure drops in non-isothermal laminar flow of power law fluids in circular tubes with various wall conditions—both constant and variable wall heat flux and temperature cases—resulted in an extended friction factor formula similar to one previously reported. In addition, an approximate friction factor formula was proposed which enables the calculation of the local friction factor when only one value of the so-called film temperature has been previously measured [55B]. The energy equation for mechanically fully developed turbulent flow between parallel plates was numerically solved taking into account the term of streamwise heat conduction. In general, the influence of the streamwise molecular conduction results in a significant decrease of the Nusselt number in the thermal inlet [17B].

The problem of heat transfer in laminar and turbulent flows of non-Newtonian fluids was examined. It was shown that in slightly non-isothermal laminar flow and in the absence of internal heat sources, the dependence of viscosity on the shear rate has little effect on the heat transfer coefficient. In addition, it was concluded that the heat transfer coefficient for turbulent flows of non-Newtonian fluids not exhibiting elastic properties can be calculated from standard equations, employing Reynolds and Prandtl numbers based on viscosity corresponding to the shear stress at the channel wall [34B]. The principal equation of conjugate statements of problems of steady state heat transfer in non-Newtonian liquids flowing along thermally stabilized zones of flat channels were examined [64B]. A monotonic differencing method was used to solve the problem of heat transfer in the flow of non-Newtonian fluids between two infinite parallel plates, where the upper plate is moving in its plane at constant velocity and the lower plate is immobile. The development of the temperature field as well as the variation in the Nusselt number and in the bulk temperature with distance from the start of the thermal inlet were addressed [78B]. Stabilized heat transfer in the flow of rheologically complex fluids in a flat channel with allowance for energy dissipation and high temperature dependence of rheological properties in the fluid was investigated. The heat transfer taking place at the outer surfaces of the channel walls to the ambient medium was assumed to obey Newton's law, and it was shown that the variation in the ambient temperature (under the condition of a constant pressure gradient) may result in a sudden change in the flow rate in the channel [35B]. An analytical solution was obtained for low Peclet number heat transfer with heat generation between parallel plates for a power law fluid. The heat transfer rate increases when fluid behavior changes from dilatent to pseudo-plastic. Positive heat generation due to viscous dissipation and chemical or nuclear reaction increases the heat transfer rate [11B]. Variance and co-variance correlations and a one-dimensional power spectrum with respect to velocity and temperature fluctuations have been measured in an anisotropic turbulent flow of air with a uniform velocity and with uniform transverse temperature gradient. Under the condition that the temperature gradient is parallel to the principal access of the turbulence stress, the vector of the turbulent heat flux and that of the pressure temperature gradient co-variance are parallel to each other; but the ratio of the two vectors is dependent upon the degree of anisotropy in the velocity field and the direction of the two vectors. The ratio of the dissipation time scale for the temperature variance to that for the turbulent energy was found to be the same as the ratio in a completely self-preserved isotropic turbulence [37B]. Heat transfer and friction in a heated turbulent gas were analyzed using a two-equation model of turbulence. Local heat transfer coefficients obtained experimentally were compared with three existing models and a modified version of one of the models predicted the decrease in the heat transfer coefficient occuring in the turbulent gas and a laminarization which occurs at local Reynolds numbers in excess of the critical value for an adiabatic flow [33B]. An experimental study of unsteady mass transfer in a pipe carrying a laminar flow of a clay suspension that exhibits non-Newtonian properties was described. The results, reduced in the form of $Sh/Sh_0 = f(Re, So)$ show that the structure properties of the fluids have a significant effect on the time to steady heat and mass transfer [85B]. Experiments made on a liquid metal turbulent channel flow under a transverse magnetic field focus on the magnetic entrance effect on the pressure drop along the channel, mean velocity profile, and turbulence fluctuation intensity. Under a dominant entrance effect, an M-shaped velocity profile is observed at high Hartmann number and the development of a flow under the uniform magnetic field is retarded by the collapse of the M-shaped velocity profile. On the other hand, when the entrance effect is weak, the flow develops slowly within a short distance from the inlet and the turbulent intensity becomes nearly zero [26B]. Correlations were presented for accurately calculating the local temperature of the walls of annuli based upon data of local heat transfer from the inner and outer tubes of annuli (heated from one or both sides) to a stable air flow. These correlations were shown to hold for high heat fluxes as well as arbitrary ratios of tube diameters and of heat fluxes at the wall, for the case of variable physical properties of the gas, assuming constant heat flux densities along the annulus [54B]. A numerical study of heat transfer to generalized Couette flow of a non-Newtonian fluid in annuli with a moving inner cylinder was applicable to the process of coating a wire with a layer of polymer [41B].

The temperature profile in a circular tube of infinite extent through which a fluid is moving under conditions of small Peclet numbers ε is determined by means of an asymptotic analysis in ε. The results show that the heated region extends an $O(\varepsilon^{-1})$ distance relative to the radius of the tube upstream of the point $\chi = 0$, and that convective effects remain important even when $\varepsilon \to 0$ [1B]. An entirely analytical solution is presented to the Graetz problem for the Dirichlet boundary condition based on a self-adjoint formalism resulting from a decomposition of the convective diffusion equation into a pair of first-order partial differential equations [56B]. The temperature at the top part of the wall of a horizontal pipe conveying a supercritical mixture of steam and water was computed from a dimensionless equation for heat transfer which corrects for the effect of buoyancy [81B]. An iterative numerical scheme was used to analyze the interactive heat transfer problem involving laminar forced convection flow in a vertical pipe and laminar natural convection boundary layer flow external to the pipe. The analysis demonstrated that the pipe Nusselt number is bounded between the values for uniform wall temperature and uniform heat flux, but that the external natural convection Nusselt number is highly sensitive and departs substantially from the uniform wall temperature results [71B]. An analysis was made for simultaneously developing laminar velocity and temperature fields in a parallel plate channel in which both convective and radiative heat transfer were taking place. One wall of the channel was heated and the other insulated as in an air-operated flat plate solar collector. The results showed that radiant interchange causes the task of convective heating of the fluid to be shared between the two walls with as much as 40% of the convective transfer taking place at the externally adiabatic wall [43B]. An analysis of laminar forced convection heat transfer in a horizontal pipe was performed for the case in which the flowing fluid loses heat to the external environment by natural convection and radiation. It was found that whereas the pipe Nusselt number is generally insensitive to the variation of the external convection coefficient, a constant Nusselt number thermally developed regime does not exist [18B]. Recent developments in convective heat transfer calculations using optimal control least-squares penalty finite elements have shown that convergence and accuracy can be better controlled by the least squares penalty formulation than by other methods [32B]. Mass transfer was studied in a two-dimensional channel with porous walls through which two species in solution were separately and uniformly injected. Concentration distributions for each solute were obtained by numerical integration of species conservation equations for $Pe \leq 300$ [58B]. The problem of mass transport for plug flow in a pipe of which the cross-section is given by a parallelogram of various side-ratios and oblique angles was solved. Tables and graphs of the eigenvalues are presented for various oblique angles and side-ratios of the parallelogram pipe [5B].

An analytical solution was obtained to the extended Graetz problem which describes wall flux, based on a self-adjoint formalism resulting from a decomposition of the convective diffusion equation, into a pair of first-order partial differential equations. The solution obtained was in striking contrast with incomplete numerical efforts in the past, and demonstrated the effect of the finite heating section condition. Although the Peclet number is the sole deciding factor for whether or not axial conduction or diffusion deserves inclusion, no global Peclet number criteria may be set for all problems [57B]. By plotting the advancing front theory in dimensionless form, it was shown that the theory can be extended to the non-reactive situation and gives a reasonable approximation for the classical Graetz and Leveque problems [75B]. A computational method was presented to calculate momentum and energy transport in two-dimensional viscous compressible duct flow. The flow in the ducts is partitioned into finite streams, and the difference equations are then obtained by applying momentum and energy conservation principles directly to each individual stream. The method was shown to be applicable to both laminar and turbulent flows [20B]. A more reliable solution was obtained to the problem of solving the transport equation for temperature including convection and diffusion in two dimensions for the thermal entry problem. This solution was obtained by using a calculation domain longer than the entry length and a flux boundary condition [8B]. A complete two-dimensional partial differential equation for developing laminar flow in a circular tube was treated by a finite-difference analysis which allowed for property variations with temperature. The continuity and momentum equation and then the energy equation are solved by direct elimination at each axial step and a marching procedure was used in the axial direction. The step-wise energy balance is rigidly satisfied throughout by using it as a constituent equation. The analysis predicts the complete developing hydrodynamic and thermal fields together with friction factors and heat transfer coefficients, and has been tested for a range of fluid velocity and thermal boundary conditions for various fluids [9B]. A generally applicable approach to developing laminar flow problems in straight ducts of arbitrary shape was presented. A three-level central algorithm which does not require iteration is used to march ahead with the solution in the axial direction. The calculation procedure can be implemented by utilizing with minor modifications any standard finite element code for linear heat conduction and several illustrated examples were presented to demonstrate the accuracy and versatility of the proposed technique [10B]. The assured spectral representation characteristics of differential operators and the method of separation of variables was used in certain cases to solve boundary value problems in transport with mixed and oblique derivative boundary conditions: these cases include (i) a cylinder cooled by a fluid flowing circumferentially around it and (ii) an infinite slab or infinite cylinder cooled by a fluid flowing along the axial direction. Solutions were obtained for both steady- and unsteady-state problems [60B]. A model was presented for heat transfer from an immersed cylinder within a packed bed of particles to gas flowing through the beds parallel to the cylinder's axis. Simplifications in the model permitted a closed form solution which agreed closely with the results of the previous numerical solution when similar correlations to the physical mechanism were employed. The results were shown to be sensitive to the values of the heat transfer coefficient at the cylinder wall [12B]. An analysis was presented to treat the heat exchanger problem between a heat-generating packed bed and an external turbulent flow using a two-dimensional model with one parameter. The analytical results agree well with previously obtained experimental data [48B]. A model was proposed for heat transfer in a turbine agitated vessel from theoretical principles based on the established flow pattern which included the contribution to the heat transfer coefficient from boundary layer mixing [4B].

Experimental studies were presented on heat transfer coefficients in two-phase cocurrent flow in a horizontal tube where liquid jet momentum was used for gas–liquid dispersion and heat transfer. Empirical equations were developed to predict the augmentation ratio of heat transfer as a function of the physical and dynamic variables of the system [50B]. The hydrodynamic and heat transfer characteristics of thin liquid films flowing in a horizontal heated channel were investigated experimentally and analytically. A physical criterion for film breakdown was formulated and incorporated into a model which successfully predicts the critical heat flux for water and organic liquids for $5 < Re < 100$ [63B]. Transient solidification of a liquid in axial flow into and through a cold rod bundle was investigated. Simple relations presented for the liquid mass displaced into or through the rod bundle were shown to be approximately consistent with experimental data [16B].

Experimental data of the critical heat flux of boiling nitrogen in horizontal tubes reported that the critical heat flux is strongly affected by the system pressure and the vapor quality whereas the effect of the mass velocity and the length to diameter ratio of the test section can be neglected. A wettability function was introduced for horizontal tubes that allows a reasonably accurate correlation with previously published results for the critical heat flux for pool boiling [7B]. An analytical study was made of the critical axial heat flux in heated closed and vertical tubes in the case of small length to diameter ratios. An expression for the central heat flux was obtained which showed the dependency of the dimensionless diameter and compared favorably with similar studies [53B]. An experimental and analytical study of heat transfer coefficients on pipe flows of hydrocarbons at transcritical pressures was performed. The experimental data yielded heat transfer coefficients to and from propane over ranges of pressure, heat flux, and Reynolds number and was compared with analytical results [36B].

Solutions to the steady advection-diffusion equation in a branching channel were obtained for both uniform and spatially varying flow fields and for two channel geometries. An interesting feature of the solutions is that anisotropy of the dispersion coefficients in the directions of the streamlines may be accounted for [22B]. The problem of the delayed arrival of a hot or cold front (relative to the flow speed) in a fluid flowing through a pipe was studied using perturbation solutions. The results provided substantiation of preliminary work which predicted that a temperature front propagates at a slower speed than the flowing fluid for small values of the Fourier number [44B]. The problem of intensifying heat exchange in the case of a nuclear reactor with longitudinal flow around the fuel rod elements was studied by applying regular microroughness to the surface of the fuel elements. Results were presented for the intensification of heat transfer and hydraulic resistance as a function of Reynolds number and the height of the protrusions [40B]. An approximate model has been recommended for calculating the non-steady temperature in a nuclear reactor channel which accounts for the height of the fuel element [77B]. Convective heat transfer of laminar mist flow was analyzed for both constant wall temperature and constant heat flux conditions. The diminishing of droplet size, the increasing of vapor velocity, and the dilution of droplet density along the tube were considered [80B]. Typical results were presented for the problem of two-dimensional steady-state heat conduction in coolant channels of different geometries subjected to the third kind of thermal boundary conditions as usually encountered in a regeneratively or dump-cooled liquid rocket engine. The solution method was based on the boundary collocation technique of linear least-squares matching using Householder reflections [76B].

The problem of drying granular solids in a fluidized bed was addressed and a description of the process was presented on the basis of mass transfer coefficients [27B]. The dependence of heat transfer upon the cross-sectional distribution of void fraction in a adiabatic two-phase bubble flow was explored experimentally. It was found that the void fraction distribution had a significant effect on the heat transfer coefficient and increasing the void fraction near the tube wall caused an increase in heat transfer coefficient [51B]. The problem of cocurrent stratified flow of liquid metal and water was investigated in a horizontal rectangular channel. A turbulence model was proposed to explain the experimental results and the analytical results showed good agreement with the experimental ones. The main results included (i) the position of the interface mainly depends upon the flow ratio of both liquids; (ii) the pressure drop is approximately proportional to the square of the average velocity of water; (iii) the heat transfer rate at the direct contact interface is several times higher than that of cocurrent flow separated by a thick solid plate [3B]. Experimental results were reported on the heat transfer and fluid friction of heated helium gas flow in a straight and helically coiled circular duct over a range of Reynolds numbers and the non-dimensional heat flux parameters. At high heating rates, a degradation of heat transfer characteristics was found to occur at local bulk Reynolds numbers well in excess of the minimum number for a fully turbulent adiabatic flow and the resulting heat transfer coefficients were much lower than those associated with the fully turbulent adiabatic flow at the same Reynolds number [47B]. The results of the study of unsteady heat transfer in the cooling of channels by water at supercritical pressure found that the reduced coefficients of unsteady heat transfer decreased with local deterioration in heat transfer. The heat transfer coefficients were determined under transient conditions produced by varying the internal heat release within the channel walls, and the temperatures of the inner surfaces of the channel were calculated by solving the inverse problem of heat conduction via the regularization technique [65B]. Both numerical and experimental studies of heat transfer in parallel nozzles with two-dimensional critical flows were extended to the case of convergent nozzles. According to the results, the critical flow rate increases with the decrease of the convergent ratio and the variation of local Nusselt numbers along the flow direction becomes small by the effect of accelerated boundary layers [28B]. The problem of the accelerated critical airflow and heat transfer characteristics in divergent nozzles in which a sonic point exists midway between the inlet and the exit of the nozzle was studied both theoretically and experimentally taking into consideration the viscous effect. The compressible laminar boundary layer equations were solved numerically using a finite difference method and a chart of the sonic line and the critical flow rate in the divergent nozzle were shown [29B]. A method for calculating visco-inertial flows of supercritical helium in circular pipes with correction for dependence of the turbulent transfer coefficient on variability of properties density fluctuations and thermal acceleration of the flow was developed. The results of the numerical calculations of heat transfer coefficients were in satisfactory agreement with experimental data and confirmed the reduction in the heat transfer coeffficient due to the non-isothermicity of the flow at different conditions [84B]. The results of an analytical calculation of turbulent flow of supercritical helium in a circular pipe under conditions of significant variability of critical properties and free convection (in uptake and downtake flows) were presented. The appearance of a wall temperature peak in the uptake flow, observed experimentally, was attributed to the transition to conditions with thermally turbulent flow [59B].

The thermal and inertial effects in turbulent flow thrust bearings was studied [61B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Literature on boundary layers deals with theoretical and experimental studies of wall boundary layers. Attention is also given to flow over a cylinder, stagnation flows, free jets and impinging jets.

Expressions have been obtained for average heat transfer coefficients for forced convection on a flat plate with an adiabatic starting length [29C]. The Blasius solution has been extended to the case of non-isothermal wall [49C]. The non-similar solutions for compressible boundary layers have been discussed [8C]. Numerical solutions are presented for the heat transfer from a non-isothermal wedge [50C]. Finite difference solutions have been obtained for the boundary layer equations [13C] and for the developing laminar flow in mixed convection [11C].

Measurements of fluctuations of velocity and temperature are reported for the thermal boundary layer downstream of a line heat source [5C]. Holographic technique is used to visualize the flow in a transition situation [7C]; the laminar separation is avoided by surface heating, while the cooling is found to destabilize the boundary layer. Shock-tube experiments are performed for heat transfer to catalytic surfaces [34C] and for end-wall boundary layer characteristics [23C]. The free-stream turbulence is found to have only a weak influence on the heat transfer in an accelerated compressible boundary layer [9C]. An experimental investigation reports the heat transfer rates on end wall and blades in a turbine cascade [19C]. Turbulent spots are measured in a heated laminar boundary layer [51C]. Flat plate heat transfer is experimentally studied in a dissociated laminar flow [14C]. Results are reported for the turbulent boundary layer with slot injection [28C].

Among other studies, an analysis that includes chemical reaction has shown that heat transfer and interfacial shear have a profound influence on the mass transfer rate from a laminar falling liquid film [54C]. A mathematical model has been developed for the propagation of an optical beam across supersonic layers [15C]; the predictions show good agreement with experimental data. Heat transfer in a flow on a continuous moving plate has been considered in [41C] and [3C]. Film cooling is investigated in [17C], while [40C] deals with non-Newtonian boundary layers. The overall resistance concept is applied to conjugate heat transfer [33C].

Several papers deal with unsteady boundary layers and stability. Numerical solutions for the transient boundary layers behind a blast are presented in [30C]. The influence of wall capacitance and resistance on unsteady heat transfer is considered [27C]. The unsteady transport processes on a flat plate are discussed in [31C] and [21C]. An exact analytical solution has been obtained for the transient heat transfer from a plate with periodic variation of temperature [46C]. Influence of oscillatory flow on wall friction and heat transfer has been considered [25C]. An analysis is made of the effect of a time-dependent entry disturbance on a free interface film [32C]. Instability of flows with heat transfer is investigated in [35C] and [24C], while the stability of a liquid layer is discussed in [22C].

A number of investigations focus on jet flows. A finite-difference model has been used for the prediction of surface discharge jets [38C]; the calculations show good agreement with experimental data. The heat transfer in a confined jet has been studied experimentally [18C]. Surface cooling by an air–water jet has been investigated in [20C]. The structure of turbulent jets has been discussed [39C]. Turbulence characteristics of plane and circular jets have been measured [6C]. Heat transfer from in-line and staggered arrays of circular jets has been measured for an extensive range of the geometrical parameters [16C].

Another topic of interest is the impingement or stagnation flow. Heat transfer in a viscoelastic boundary layer at a stagnation point has been considered [43C]. Also, the stagnation point behavior of a micropolar fluid has been studied [45C]. An investigation of heat transfer to a non-Newtonian fluid at an unsteady stagnation point appears in [44C]. Cooling of a surface by a water jet has been considered [26C]. A finite-element analysis deals with the impingement of a free jet [36C]. Mass transfer coefficients have been measured by the naphthalene sublimation technique for an obliquely impinging circular jet [42C]; the point of maximum mass transfer is found to be displaced from the point of geometrical impingement.

Heat transfer from spheres, cylinders, and other bodies has stimulated some investigations. Particle-to-particle heat transfer in a fluidized bed is considered in [52C]. Heat transfer from a particle-laden gas flow has been studied [10C]. An investigation considers the heat transfer from a bed of heated spheres to a slowly moving fluid [2C]. Conjugate heat transfer from a droplet in a creeping flow has been studied [1C]. An experimental investigation has led to an empirical correlation for the effect of the finite length on the heat transfer from cylinders [37C]; for a length-to-diameter ratio of 4 or more, the finite length is found to have little effect. Conjugate heat transfer from a cylinder in low Reynolds number flow has been analyzed [47C]. A simplified model has been presented for heat transfer from a cylinder in a packed bed [12C]. Heat transfer from a tube bank is considered in [4C]. A study deals with the asymmetric boundary layer on a non-isothermally heated cone [53C]. An experimental investigation is reported on the heat transfer from a rectangular body to an external flow at various angles of attack [48C].

FLOW WITH SEPARATED REGIONS AND THROUGH POROUS MEDIA

Separated regions

Turbulent shear stress and heat flux measurements [26D] in a separated and reattached flow over a cylinder with plane leading surface demonstrate that downstream of the reattachment line heat transfer develops much faster than momentum transfer. The same observation was made on a cylinder in axial flow with a conical nose [18D] and with a blunt leading configuration [13D]. A computer calculation [4D] of turbulent heat transfer downstream of an abrupt pipe expansion using the h/ε model for turbulence and a transition function for the near wall region resulted in generally encouraging agreement with experiments. Correlations have been developed [20D] for convective heat transfer at backsteps, open cavities, and cylinders in plane supersonic separated flow. Measurements on a row of four inline cylinders [1D] revealed that the heat transfer for forced flow changes drastically at a critical Reynolds number $Re_d = 1.14 \times 10^5(c/d)^{-5.84}$ with c denoting the distance of the cylinders and d the diameter. Correlations were presented [16D] for continuous heat and mass transfer to spherical solids and bubbles in a flow field with high turbulence intensities. Relations are presented based on shear velocity.

Measurements [28D] of convective heat transfer on a plate from an impinging round hot gas jet found that at $x/D > 8$ the jet turbulence augments heat transfer. Two secondary peaks were found [27D] on the heat transfer distributions at a flat plate from a circular impinging jet at a small distance of the nozzle. The outer peak was caused by transition to a turbulent boundary layer and the inner one by turbulence in the jet. The scaling laws [25D] for the center line temperature and velocity of a heated jet discharged vertically into an ambient of uniform temperature were derived from dimensional analysis. Experimental data [21D] were reported for heat transfer from a heated and ventilated plane jet tangent to a plane wall. A computer analysis [22D] describes heat transfer from a gas jet to a porous baffle. Local heat transfer was measured [6D] for an array of round impinging jets with one-sided exhaust of the spent air. The paper reports also a relation of the optimum between the open surface of the perforations and the spacing with regard to heat transfer and pumping power. Experiments [17D] indicate that mass transfer from a gas flow to an array of liquid jets is about 30% higher than mass transfer for flow normal to a solid cylinder at $Re \sim 10$ and that the difference becomes smaller at higher Reynolds numbers.

A new finite-element formulation for convection–diffusion problems [2D] with three-node triangular elements and control volumes avoids difficulties of other methods.

Porous media

An analysis [9D] of heat and mass transfer in fixed beds at low Reynolds numbers agreed well with measured data when based on a realistic bed geometry model. A paper [10D] summarizes heat and mass transfer in packed beds. The electrochemical method was used (5D) to study overall liquid–solid mass transfer in packed beds with upward cocurrent gas and liquid flow. The results are compared with data obtained by other techniques. Experiments and analysis [32D] considered steady non-isothermal liquid flow and heat transfer in sintered fibrous metallic wicks. A closed form solution [24D] was obtained for the unsteady convective heat transfer in a porous medium after a step change of the inlet temperature of the fluid. An analysis [29D] considered buoyancy induced transport in a porous medium saturated with pure or saline water at temperature levels at which the density goes through a maximum. Two-phase, two-component heat and mass transfer in a porous medium subject to a fire was analyzed [30D] and the results are compared with experiments on an alumina powder system. A computer analysis considered moisture migration caused by temperature differences in an unsaturated porous medium with no mass flow through its surfaces for a step change of the temperature of one surface [7D] or for a periodic temperature fluctuation of one surface [8D]. Multi-phase moisture transfer in a drying porous medium considers the dependence on material characteristics [15D].

Fluidized beds

Measurements [31D] of the temperature distribution at the bed inlet and outlet are used to obtain heat transfer coefficients between the particles and the fluid in a fluidized bed. The coefficients are found to vary with bed height, particle diameter, and fluid velocity. A change of flow from bubbling to turbulent was observed [33D] to occur in fluidized beds. Heat transfer to immersed tube banks was also studied. An analysis [14D] considers heat and mass transfer from solids to a rising bubble in a fluidized bed used for drying granular solids. A model proposed by Gabor was used [19D] to predict radiative contribution in a high temperature fluidized bed.

Experiments [12D] were carried out in an air-solid fluidized bed to determine heat transfer to a horizontal tube. Available correlations were found inadequate to predict the measured data. Surface roughness can increase heat transfer from horizontal immersed tubes to a fluidized bed by up to 40% [11D]. Local heat transfer coefficients were found [3D] to change strongly around the periphery of horizontal tubes in air fluidized beds. The mean heat transfer coefficient increases with decreasing particle size and increasing system pressure. Previously reported correlations were found unsatisfactory. The solidity of heat exchangers for coal-fired fluidized beds can sometimes be significantly increased without degradation of the fluidization according to [23D].

TRANSFER MECHANISMS

Much of the published work related to transfer mechanisms is concerned with turbulent flow. A surface rejuvenation model is used to obtain the universal laws of the velocity and temperature distribution near a wall [23E]; the predicted results show good agreement with experimental data for different values of the Prandtl number. A theory of thermally induced surface fluctuations on simple fluids has been developed in [11E]. The homogenization of a transport process is discussed in [18E], while the influence of initial conditions on the properties of Burgers' turbulence is studied in [14E]. The temperature fluctuations resulting from grid-generated turbulence are investigated in [21E] and [24E]. The skewness of the temperature derivative is discussed in [20E]. A new variational principle is proposed for unsteady heat and mass transfer processes [19E]. The velocity and temperature fluctuations have been measured by a hot film probe placed in a flow of mercury [5E].

Among other studies related to transfer mechanisms, the flow processes and heat and mass transfer in fluidized beds have been investigated [3E, 12E]. Ignition and flame quenching of solid fuel dusts are considered in [2E], while results on the turbulent exchange in gas diffusion flames are presented in [17E].

Many papers deal with the transport processes on the molecular or atomic levels. Numerical treatment of free-molecular pure diffusion is outlined [13E]. A theoretical study is made of stagnation heat transfer by accounting for molecular vibrational relaxation [15E]. The transfer mechanisms in molecular Knudsen gas are considered [9E]. A discussion has been presented on a Ginzbourg–Landau constitutive equation for fluctuating heat flux [7E]. A statistical theory is developed for the thermal conductivity of composite materials [16E]. The thermodynamic implications of nonlinear constitutive relations in gasdynamics are discussed in [25E]. An analytical study deals with the molar and molecular processes of heat and mass transfer at high pressures and temperatures [6E].

Other investigations are concerned with a variety of transport mechanisms. An analysis has been made of moisture migration caused by temperature gradients in a porous material [4E]. New solutions are presented for the thermal diffusion effects in a boundary layer on a catalytic surface [22E]. Laminar flow dissolution and diffusion in a non-Newtonian fluid is considered in [10E]. Heat transfer coefficients for gas–solid transport in a pneumatic system have been presented [8E]. Attention is given to the rate of heat and mass transfer from a small particle that is freely suspended in a linear shear field [1E].

NATURAL CONVECTION—INTERNAL FLOWS

Natural convection in open and closed cavities continues to draw substantial attention. As has been true for at least a decade, there are many papers on various aspects of convection in horizontal layers heated from below. There is also interest in related problems of natural convection in inclined plane layers and in plane and other layers with volume heat sources. Papers on natural convection in cylindrical cavities with either horizontal or vertical axes are also in plentiful supply. Related phenomena which have been studied during the past year include combined heat and mass transfer, convective flows involved in melting and solidification, flows in porous media, capillary convection, and mixed natural and forced convection.

For a horizontal layer heated from below, experiments indicate the influence of very large variation in fluid viscosity across the layer; use of the properties at the mid-plane permits application of constant property solutions for both the critical Rayleigh number and the initial variation of Nusselt number above this critical value [1F]. Speckle photographs show constant velocity contours in a layer at low Rayleigh number [37F]. Very high Rayleigh number experiments [18F] show that the Nusselt number varies closely as $Ra^{1/3}$. Velocity and temperature profiles taken under turbulent thermal convection conditions seem to indicate agreement with previous studies [62F]. The onset of Rayleigh–Benard convection in horizontal layers was studied by considering random fluctuations within the fluid layer [27F].

Numerical analysis of convection in a shallow water layer with heating from an array of horizontal cylinders indicates a uni-cellular flow [66F]. Thermal instability in a micropolar fluid layer subject to transverse magnetic field has been analyzed [48F]. Galerkin technique [72F] is used to study the convection in the earth's mantle, where $Pr \simeq 10^{23}$.

Several studies consider the influence of thermal boundary conditions on convection in a horizontal layer primarily for conditions of nearly insulating boundaries—that is a Biot number based on layer thickness and fluid conductivity that is very small [51F]. In the limit of very low Prandtl number, a square pattern of convection cells is indicated [4F]. Large-scale motion for a low Prandtl number fluid is predicted [7F]. Another study considers all boundaries of the layer adiabatic except the bottom surface which has a variable temperature [29F].

Measurements of the velocity distribution in a horizontal layer show that flow regimes leading to the onset of turbulence are dependent on both aspect ratio of the layer and Prandtl number [19F]. The influence of aspect ratio on stability for both internal heating and heating from below has been demonstrated [17F]. An analysis of transient natural convection in a cavity containing water shows the importance of the maximum density point at 4°C [64F].

The influence of variable vertical spacing with a flat upper wall on thermal convection has been examined [12F]. A Wollanstan prime interferometer is used to study the heat transfer in triangular enclosures either heated or cooled from below [16F]. An analysis of convection in a trapezoidal enclosure [24F] agrees well with experimental measurements [25F]. Natural convection as it affects flow in rooms with small ventilation openings has been studied experimentally and numerically [20F].

Flow visualization in inclined air layers heated from below correlates well with heat transfer measurements [55F] and analysis [54F]. The influence of aspect ratio in a rectangular-shaped honeycomb on the critical Rayleigh number has been studied at different angles of inclination [59F].

With volume heat sources in a fluid layer, the layer may tend to be partially stable and partially unstable depending on the boundary conditions at the top and bottom surfaces. For an insulated lower boundary, a higher Nusselt number is observed for rigid–free velocity boundary conditions as compared to rigid–rigid boundary conditions [15F]. An analytical model predicts the form of relationship with Nusselt number as a function of an internal Rayleigh number and Prandtl number [8F]. For non-uniform heat generation, a linear stability analysis has been performed on a layer with a free surface [71F]. An eddy diffusivity model shows asymmetries with respect to the mid-plane when thermal radiation is significant in a layer heated from below [9F].

Characteristics of convection in a heat-generating fluid contained in a rectangular cavity with cooled side walls indicate the primary flow is bi-cellular circulation [2F]. With different thermal boundary conditions on the side walls, the heat flux in heat generating fluids has been examined using an interferometer [63F]. The temperature distribution following a step change in volumetric heating has been determined [35F].

Several studies examine convection in the annulus between two horizontal cylinders maintained at different temperatures. The development of cellular motion has been predicted in an annulus of fairly small thickness [65F]. Boundary layer approximation to the flow in the annulus appears to agree well with earlier numerical and experimental results [28F]. Numerical calculations over a range of Prandtl number and diameter ratios provide local and average heat transfer results [34F]. A related study [33F] of convection around a single cylinder indicates the problems in using simple boundary layer models. For slightly eccentric annuli, the heat transfer can be predicted from solutions for concentric annuli by a simple radial coordinate transformation [68F]. A correlation [52F] for boundary layer convection dependence upon Prandtl number may be useful within a large annulus.

Both single cells and double cells are found in the convective flow of a layer held between two spheres maintained at different temperatures [6F]. The numerical solution [58F] for such a convective flow agrees well with earlier experimental results. A visualization system has been used to show the flow in the cavity formed between an external spherical enclosure and different shaped bodies within the enclosure [46F].

Temperature and velocity distributions have been measured in a horizontal cylindrical cavity with the ends maintained at different temperature [30F]. Unsteady natural convection has been examined in a rectangular cavity with one side wall heated and the other side wall cooled [45F].

Special numerical techniques have been used to show the stability of convection up to a very high Rayleigh number in a differentially heated cavity [32F]. An analysis [39F] and an experiment [38F] consider the convection in adjacent vertical rectangular channels as would apply in certain solar energy systems.

Several papers have appeared on natural convection in vertical cavities. One considers a transient laminar flow field in a converging vertical channel [26F]. The effects of radiation on convection in a vertical channel have been examined [61F]. The instability of convection in the annulus between coaxial vertical cylinders has been examined [67F]. Another study [10F] predicts the breakdown of the conduction regime in a vertical annulus into multi-cellular flow.

Natural convection generally plays a significant role in determining the melting volume and local heat transfer around a heater immersed in a potentially melting solid. The importance of such natural convection around a horizontal heater has been demonstrated [69F]. The effect of the maximum density point of water on the convection of a melting ice layer has been measured. In freezing on a vertical surface, natural convection can also be very important [70F].

Rotation as well as gravity can supply the body force for natural convection. Several flows in rotating heated cavities have been studied analytically [47F]. A study of combined convection and radiation heat transfer in a rotating fluid considers the effect of radiation on stability [41F]. Rotation in a magnetic field has been studied with low amplitude thermal convection [60F].

Natural convection in saturated porous layers has been reported on with greater frequency in the past few years. Studies include analytical and experimental work on stability, convective flow patterns, and heat transfer in such layers. Lower bounds of the critical time for the onset of convection following a sudden rise in bottom surface temperature of a porous layer have been shown to be best determined by the energy method [5F]. Another study on the stability of flow in a porous medium following sudden heating includes the influence of distributed heat sources [53F]. The evolution of unsteady flow has been followed in a porous layer [23F].

An analysis indicates the onset of convective heat transfer in a vertical porous cavity heated from below [3F]. The onset of convection in a layered porous medium is quite similar to that in a homogeneous layer [35F].

The study of convection in a porous layer having an exothermic decomposition reaction at the bottom portion of the layer shows a thermal front passing through the layer [56F]. Convection due to a point source in a fluid saturated medium has been studied numerically [22F]. In a two-component fluid-saturated porous medium heated from below, the Soret effect appears to stabilize the layer [44F].

In a double-diffusive convection, two gradients—thermal and concentration—can drive the flow. Applications of such a flow in stellar bodies where the Prandtl number is very small have been examined [50F]. A transformation is used to show in a simple form the influence of the Soret and Dufour effects on convection [31F]. Instability in double-diffusive convection in an inclined layer has been examined analytically [43F] and with a flow-visualization system [42F]. The merging of layers in the early stages of double-diffusive convection has been demonstrated [49F].

Surface tension or capillary effects can influence convection in layers with free surfaces. Energy theory can predict the stability of such layers [11F]. Criteria for the instability of a spherical shell indicates the importance of surface tension forces [21F]. Experiments on capillary driven convection show the streamline flow about a growing crystal [57F].

Combined free and forced convection—also called mixed convection—can occur in cavities or channels. Turbulent effects have been measured [40F] in the channel formed between two vertical parallel plates. On one plate there is opposed flow while on the other side there is aiding flow. A mixed flow in the entrance region of a vertical annulus shows potential flow reversal with either aiding or opposing flow [14F]. Measurements show the different flow regime of mixed convection in a heated horizontal tube [13F].

NATURAL CONVECTION—EXTERNAL FLOWS

The method of using the local similarity solution of a free convection boundary layer was used to study steady two-dimensional conjugate heat transfer problems of free convection from a vertical flat plate. The effects of axial conduction in the flat plate on the interfacial temperature were significant in the case of constant heat flux at the outer surface of the flat plate [28FF]. An analytical study of laminar natural convection on both sides of a vertical conducting wall of finite height separating two semi-infinite fluid reservoirs of different temperatures reported representative streamlines and temperature and heat flux distributions [3FF]. A study of natural convection flow arising from a steady line thermal source embedded at the leading edge of a vertical surface was performed for moderately large values of Grashof number by the method of matched asymptotic expansions. Results presented for prescribed wall temperature and for an adiabatic convective wall plume showed that the structure of the wall plume depends strongly on the location of the horizontal plane [1FF]. Natural convection heat transfer from the face-to-face surface of parallel, square vertical plates was investigated experimentally. The experiments encompassed three types of hydrodynamic conditions along the lateral edges—fully open, blockage of one edge gap, blockage of both edge gaps—and the results obtained differed from those accepted in the literature [44FF]. The effect of a buoyant boundary layer spawned by a heated vertical plate on the natural convection heat transfer from an upper colinear vertical plate was determined analytically. Heat transfer at the upper plate was found to be affected both by the preheating and by the finite velocity imparted to the fluid by the first plate, respectively tending to degrade and to enhance heat transfer [46FF]. Local similarity and local non-similarity methods were applied to analyze the effects of buoyancy-induced streamwise pressure gradient on the momentum and heat transfer characteristics in the laminar boundary layer adjacent to a continuous, moving horizontal flat plate [8FF]. The combined buoyancy effects of thermal and mass diffusion on the heat and mass transfer characteristics of a laminar boundary layer adjacent to a continuous plate moving in a vertical or inclined direction through a quiescent ambient fluid was studied analytically. It was found that for the thermal boundary assisting condition, the wall shear stress and the surface heat/mass transfer rates are further increased when the buoyancy force from mass diffusion assists the thermal buoyancy force. Numerical results were presented for the local Nusselt number and the local Sherwood number for diffusion of common species into air and water [47FF, 10FF]. The buoyancy force effects on the heat transfer characteristics of the laminar boundary layer adjacent to an inclined, continuous flat sheet that moves in a fluid at rest were examined analytically. The results showed that a positive buoyancy force contributes to an increase in the local friction factor and the local Nusselt number [29FF]. Basic heat transfer results for natural convection in an array of vertical in-line plate segments were obtained by numerical finite difference solutions and compared to previously computed results for staggered and continuous plate arrays. Results included enhanced heat transfer rates by as much as 90% for fixed values of the wall to ambient temperature difference and heat transfer in the discrete plate array configurations [36FF].

A numerical analysis based on the integral equations of momentum and energy was performed to determine the distribution of velocity and temperature and a heat transfer coefficient for the problem of natural convective heat transfer from an arbitrarily curved plate. The specific case addressed was natural convective heat transfer from the inner surface of an isothermal plate whose leading edge is located vertically and whose end edge is horizontal and is subjected to a variation in the gravitational component in air [26FF]. Data obtained from a heat transfer experiment of a vertical falling liquid film provided new correlations for the heat transfer coefficient for moderate and low Reynolds numbers cases. The results reconfirmed the classification of flow regimes of falling liquid film previously proposed. In addition, it was concluded that the turbulent boundary layer theory was applicable only to high Reynolds number regions (greater than 10^3) and that for moderate and low Reynolds number regions the flow cannot be represented by the concept of eddy diffusivity [24FF].

A numerical solution to the Navier–Stokes equations for laminar natural convection about a horizontal isothermal circular cylinder was provided for $10^0 \leq Ra \leq 10^7$. The flow was shown to approach natural convection from a line heat source as $Ra \to 0$ and laminar boundary layer flow as $Ra \to \infty$. It was concluded that boundary layer solutions do not adequately describe the flow and heat transfer at low and moderate values of Ra because of the neglect of curvature effects and the breakdown of the boundary layer assumptions in the region of the plume [27FF]. Laminar natural convection heat transfer from the outside surface of a uniformly heated cylinder (constant heat flux condition) was investigated experimentally at different angles of inclination of the cylinder. General equations for the effect of inclination were determined for both the local and average heat transfer coefficients which increased with the angle of inclination of the cylinder [2FF]. The transverse curvature effect on the heat transfer in the turbulent natural convection flow from the outer surface of a slender vertical circular cylinder was studied by an improved integral method for various values of Prandtl numbers and for various values of transverse curvature parameter [30FF]. The onset of transient natural convection from a suddenly heated horizontal cylinder of finite diameter was studied both numerically and experimentally. The termination of the initial conductive and "locally" convective heat transfer regime which precedes the onset of global natural convection was treated as a thermal stability phenomenon and confirmed experimentally [32FF]. The naphthalene sublimation technique was used to perform experiments to determine the natural convection heat flux distribution on the faces of isothermal circumferential fins affixed to a horizontal heated (or cooled) tube. The findings suggested that the highest heat transfer coefficients occur adjacent to the periphery of the fin while the lowest is at the inner portion of the fin adjacent to the tube. These results are in contrast to the conventional model which assumes a uniform heat transfer coefficient across the face of the fin [45FF].

The problem of free convective flow from a heated sphere in the Boussinesq approximation at high Grashof number was studied numerically. The characteristics of the boundary layer close to the surface of the sphere were evaluated and the eruption of the fluid from the boundary layer into the plume above the sphere demonstrated that only far away from the surface of the sphere may the heated sphere be treated as a point source of heat [35FF]. The development of the boundary layer formed from a buoyancy-driven asymmetric water boundary layer along a heated cylinder was studied under two heating conditions—constant wall heat flux and constant wall temperature. In general, it was found that close to the leading edge, the magnitude of the secondary flow is small and the boundary layer flow is forced convection dominant. The secondary flow grows downstream, the interaction of the free and forced convection becomes important, and the flow becomes free convection dominant further downstream. The temperature dependent viscosity of water has the effect of thinning the heated boundary layer and thus the buoyancy effect and the variable viscosity effect enhance each other over the lower part of the cylinder and compete with each other over the upper part [51FF]. From experimental results, vertical distributions of temperature heat flux densities and heat transfer coefficients were determined for free convection heat transfer from a vertical thin wire to air. The results are in good agreement with those predicted by the approximate integral method taking into consideration the variation of electrical resistance with temperature [15FF]. A numerical analysis was presented of the boundary layer equation with curvature effect terms for free convection about a sphere in air and a simple expression for the average heat transfer coefficient was proposed. The results confirmed the role of curvature effect terms in the continuity equation and in the energy equation is dominant as far as heat transfer is concerned [14FF]. The axisymmetric plume that arises from the point heat source affected by the existence of an externally induced flow aligned with the plume flow was studied for the two Prandtl number values of 7 and 0.7. Of particular interest was the effect of the velocity field on the centerline temperature and the boundary layer thicknesses [4FF].

The series of several variables was applied to the solution of the boundary layer equations of free convection in laminar three-dimensional systems. Temperature profiles obtained from numerical computation were compared with experimental data for the case of free convection over an inclined circular cylinder [48FF]. An analytical expression for the heat transfer coefficient for a high Prandtl number fluid in turbulent natural convection adjacent to a heated vertical surface was presented which compared favorably with previous numerical studies [39FF]. A study of the boundary layer behavior in transient turbulent thermal convection flow concluded that the behavior of the thermal boundary layer is quite different from the corresponding steady-state behavior. This deviation may be an indication of the fact that the effect of flow restructuring in the turbulent core region is not negligible upon the thermal boundary layer [11FF]. A comparative study was performed of the stream function–vorticity formulation and penalty function formulation for natural convection in an enclosure. Numerical results were presented for several geometries, boundary conditions, and the effects of Rayleigh number and Prandtl number on the flow and heat transfer [37FF].

Using a time dependent numerical model, the anelastic–liquid equations were solved in two dimensions and a systematic investigation of compressible convection was presented using an approximate set of equations derived for a compressible liquid of infinite Prandtl number. Both marginal stability and finite amplitude convection were studied and it was concluded that a single parameter defined as the ratio of the depth of the convecting layer d to the temperature scale height of the liquid H_P governs the importance of the non-Boussinesq effects of compressibility, viscous dissipation, variable adiabatic temperature gradients, and non-hydrostatic pressure gradients. When $d/H_P \ll 1$, the Boussinesq equations result; when $d/H_p = O(1)$, the non-Boussinesq terms become important [25FF].

An analytical study was performed of a combined free and forced convection boundary layer problem with the two flows perpendicular to each other. The problem was formulated for flow over a wedge and results were presented for different Prandtl numbers over a range from forced convection dominant to free convection dominant flow [13FF]. The problem of laminar combined free and forced convective heat transfer with blowing along an isothermal vertical wall was studied. Special attention was given to clarify the limits between the combined convection and the effectively pure (either forced or free) convection [49FF]. The periodic vortex formation in combined free and forced convection was visualized experimentally using smoke. The shroud of heated air formed around an approximate point heat source was modeled by an expanding spherical vortex [41FF]. The boundary layer equations of mixed convection were examined in the vicinity of a point of zero skin friction. The correlation between the uniform wall temperature case and that of the compressible boundary layer flow was outlined, and it was concluded that the Goldstein–Stewartson theory is appropriate for this case. In addition, the case of a uniform heat flux wall was examined theoretically. Significantly, it was concluded that the original Goldstein–Stewartson theory was also sufficient to describe the structure of the singularity at the separation in this case. Indeterminancies associated with the theory were determined via a reconciliation between an analytical and a numerical representation of skin friction and heat transfer coefficients near separation [21FF].

The combined effects of buoyancy forces from thermal and mass diffusion in a laminar boundary layer adjacent to a continuous, horizontal flat plate moving through an otherwise quiescent fluid was studied analytically by the local non-similarity method of solution. In general, it was found that wall shear stress and the surface heat and mass transfer rates increase with increasing thermal boundary force [7FF]. An analytical study was performed to examine the heat and mass transfer characteristics of natural convection flow along a vertical cylinder under the combined buoyancy force effects of thermal and species diffusion. Parameters varied during the study included cylinder curvature, surface boundary condition, Prandtl and Schmidt numbers, thermal and concentration Grashof numbers, and the relative buoyancy force effect between the species and thermal diffusion [9FF]. The conditions marking the onset of vortex instability in mixed convective flow over an inclined surface in a saturated porous medium were investigated by means of a linear stability analysis. The problem was solved numerically for the cases of (i) and inclined surface at constant wall temperature with free stream velocity at zero angle of incidence to the inclined surface and (ii) an inclined surface with constant heat flux with free stream velocity at 45° with respect to the inclined surface. Results showed that the effect of external flow is to suppress the growth of vortex disturbances in both aiding and opposing flows. For the same value of the mixed convection parameter, the opposing flow was found to be more unstable than the aiding flow [20FF].

A regular perturbation analysis was presented for three laminar natural convection flows in liquids with temperature dependent viscosity: (i) a freely-rising plane plume, (ii) the flow above a horizontal line source on an adiabatic surface, and (iii) a flow adjacent to a vertical uniform flux surface [6FF]. Numerical results were presented for the transient and steady-state velocity field, temperature field, and heat transfer characteristics for natural convection at a heated vertical plate in air accounting for internal heat generation and variable properties. One result indicated was the 30% enhancement of the wall heat transfer coefficient in the variable fluid properties case as opposed to constant properties case [50FF].

An equation was provided for predicting the combined convection heat transfer rates to power law fluids for the simple situation of flow past an isothermal vertical flat plate [42FF]. The correlating equations for combined laminar forced and free convective heat transfer to Newtonian fluids was extended to the case of visco-elastic fluids. The results of the analysis found that the effect of visco-elasticity is to increase the Nusselt numbers, especially at higher Prandtl numbers, and that in the stagnation region of a heated horizontal cylinder, natural convection constructively acts to increase the Nusselt number and thus ameliorates the heat transfer [43FF].

The problem of three dimensional thermal instability over a horizontal ice cylinder which occurs in a minimum heat transfer region was solved numerically. The appearance of a convexo-concave melting front which was predicted from experiment was explained by the convection pattern along the cylinder. The transient process of onset of stable vortices around a cylinder was clarified by streamlines and isotherms [40FF]. Experimental data were presented for the onset of manifest convection in water around a heated cylinder. Thin nickel coatings were applied to three Plexiglas cylinders of different diameter, and the nickel surface was used as a heater. Observations made by a holographic interferometer showed that initially conduction prevailed but after a period of time the manifest convection was detected around the cylinder [17FF]. Flow visualization and temperature measurements were used to study conditions in shallow water layers heated from below by cylindrical sources and cooled from above by an air interface. For Rayleigh numbers between 10^5 and 10^6, experiments were performed for a single horizontal cylinder and for an array of five cylinders which demonstrated that the free convection boundary layer which develops on the cylinder is without separation [23FF]. The results on an analytical/experimental study of submerged buoyant fresh water and salt water jets injected horizontally into a quiescent unstratified reservoir showed that fresh water jets of a fixed exit Froude number penetrated to a greater horizontal distance before surfacing as the temperature of the reservoir was lowered. Salt water jets of a fixed exit Froude number penetrated shorter horizontal distances into the reservoir as the same concentration was increased. The dependence of the flow characteristics upon temperature and salt concentration was shown to be a significant factor contributing to the wide discrepancy in previously reported data [38FF]. A linear small perturbation method was applied to the problem of cellular convection in minute droplets on a heated solid surface. It was concluded that (i) larger values of the Biot number lead to greater stability, (ii) a hemispherical droplet is more stable under surface tension variations than a flat liquid layer, and (iii) a parabolic steady thermal profile is more susceptible than a linear one to thermal disturbances due to surface tension force [18FF]. Experiments of free convection heat transfer from electrically heated platinum wires and a platinum strip to supercritical carbon dioxide demonstrated that the heat transfer can be predicted by a conventional Nusselt type correlation if the dimensionless numbers are based on integrated thermophysical properties [31FF]. An experimental study of free convection heat transfer from a copper sphere to supercritical helium presented empirical correlations accurate to $\pm 20\%$ between Nu, Pr, Gr, $\rho_b \Delta\rho$, T_b and ΔT. A boiling-like phenomenon was observed experimentally near the critical point in that the heat transfer coefficient h increases with temperature difference until h reaches a maximum after which h decreases for large ΔT [19FF]. Experiments conducted on the heat transfer from internally heated $ZnSO_4$–H_2O pools in curved surfaces extended the existing data for non-boiling pools to higher Rayleigh numbers. The data for convective downward heat transfer from non-boiling pools to a curved surface were reasonably close to the Mayinger correlation extrapolated to higher Rayleigh numbers and lower ratios of pool depth to the radius of curvature. Sideward heat transfer to a surface could be described by $Nu = 0.7Ra^{0.2}$ [16FF].

Experimental results quantified the fact that when a vertical ice surface melts into a stable salinity gradient, the melt water spreads out into the interior in a series of nearly horizontal layers. A puzzling feature of the results is the relatively weak dependence of the layer scale on local salinity, though the vigor of convection and the rate of melting are greater when the salinity is high [22FF]. Calculated numerical results were presented from laminar buoyancy induced flows driven by thermal transport to or from a vertical isothermal surface in cold pure pure and saline water wherein a density extremum arises. Buoyancy force reversals were shown to arise for a vertical ice surface at 0°C melting and fresh water between 4 and 8°C at atmospheric pressure. Temperature conditions for which buoyancy force reversals occur are of special interest because of the resulting anomalous flow behavior and low surface heat transfer rates. The transition from conditions with no buoyancy force reversal to those resulting in a large buoyancy force reversal is accompanied by as much as 50% decrease in surface heat transfer [5FF]. The intradiurnal heating and cooling cycle of the mixed layer of the tropical ocean was investigated through the use of a pseudo-two-dimensional numerical model. Particular emphasis was given to two-component diffusion resulting from dynamic instabilities in the water column. The resulting Rayleigh numbers indicate the possibility of double diffusive convection whereby the vertical transfer to salt and heat may proceed at rates far greater than can be accounted for by molecular diffusion alone [12FF]. The concept that the usual Navier–Stokes equations are not suitable for studying the flow of water at 4°C was extended to include the problem of unsteady free convection flow of water at 4°C past an infinite vertical plate following a depth change in temperature of the plate. It was found that the skin friction increases due to the increase of the temperature of the water when the plate is being cooled, and decreases when the plate is being heated due to free convection currents. The rate of heat transfer increases with the increase of the temperature of the water in both the cooling and heating cases [34FF]. The finite element scheme proposed by Galerkin was used to explore the effects of thermally induced property changes during the extrusion of a flowing, molten polymer. A new phenomenon, thermal extrudate swell, was discovered and it was found that extrudate expansions up to 70% of the die diameter may occur in a Newtonian fluid with thermal properties similar to those of low density polyethylene [33FF].

CONVECTION FROM ROTATING SURFACES

The temperature distribution was calculated [8G] for flow around a rotating disk including the effect of viscous heating. Buoyancy effects were analyzed [6G] for laminar flow and heat transfer on rotating hemispherical bodies in the range $0 < Gr/Re^2 < \infty$ and $0.72 < Pr < 100$. Natural convection mass transfer to

Newtonian and non-Newtonian fluids from rotating vertical cylinders could be described [4G] by the following equation: $Sh\,Sc^{-1/3} = 0.62fRe$ with f indicating the friction factor for a Schmidt number varying between 2.6 and 32,000 and a Reynolds number between 10^2 and 10^5. Mass transfer to non-Newtonian fluids was found to be lower than what would be predicted by the Newtonian relation. An analysis [3G] considered natural convection in a rotating spherical annulus with a uniform gravitational field parallel to the axis of rotation for Reynolds and Prandtl numbers larger than those studied before. A numerical solution [9G] describes laminar developed heat transfer in a rotating cylindrical tube for a wide range of Prandtl numbers. Heat transfer between eccentric rotating cylinders was also analyzed [5G]. Mass transfer experiments and analyses were published for rods and plane strips rotating around an axis normal to their length dimension [2G]. Particle motion in the flow around pitched blade turbines was observed [7G] stereoscopically. The spiraling flow of a viscous compressible gas surrounding a rotating porous cylinder with fluid ejection was calculated [1G].

COMBINED HEAT AND MASS TRANSFER

Much of the activity in combined heat and mass transfer continues to relate to film cooling and transpiration cooling. Interest in such flows comes, to a great extent, from the development of high temperature gas turbines. Today, most high performance engines use film cooling as well as other techniques for maintaining reasonable temperatures in the high temperature stages, certainly with stationary blades if not with the rotating blades as well. This film cooling usually occurs with a row or a series of rows across the span of the turbine blades, often in the stagnation region and sometimes along the pressure and suction sides of the blade as well. In addition to film and transpiration cooling, heat transfer to impinging jets, and combined heat and mass transfer in porous media has been studied.

Experiments on the influence of injection hole spacing and orientation with a single row of injection holes appear to agree with earlier studies [5H]. With two rows, one downstream of the other, a staggered pair of rows is better than an in-line pair [1H]. The use of ammonia injected from a turbine rotor blade surface with ozalid paper along it shows the jet flow attachment on a rotating system downstream of the film cooling holes [4H].

Injection of a film coolant can produce a loss in the aerodynamic efficiency of a gas turbine stage. An analysis of such loss considering the mixing of jets with the freestream agrees well with measurements of the head loss in the flow through a cascade [10H].

With full-coverage film cooling, there is an array of injection jets along the whole surface of the wall to be cooled. In the limit with increasing hole density per unit area (and of course decreasing hole size) full-coverage film cooling would approach transpiration cooling. The velocity fluctuations and turbulent shear stress have been measured [19H] in the region of full-coverage film cooling while a model [20H] predicts the flow recovery downstream of the injection region. Measurements of the average heat transfer in this system [2H] were correlated by a numerical procedure [3H]. Another study of full-coverage film cooling on a turbine blade indicates the cooling effectiveness as the system approaches transpiration cooling [7H].

Film cooling is used elsewhere in gas turbine systems, for example, in the combustor section. There, where the flow can approximate a two-dimensional film cooling more closely than on a turbine blade, the design of the slot geometry is still very important. The turbulent mixing that can occur following injection tends to decrease effectiveness [17H].

An analysis [12H], using a series expansion, finds the maximum heat transfer was not at the stagnation point for an axisymmetric flow with mass transfer. Analytical approximations have been developed to predict the heat transfer with transpiration cooling into a laminar boundary layer using different injection gases [11H].

Ablation cooling is used for protecting vehicles entering a planetary atmosphere. One study for the Galileo probe, which will be used in exploring the Jovian atmosphere, shows how turbulence can permit significantly increased surface radiation [13H].

An array of jets impinging on a surface containing vents to remove the spent airflow, gives higher heat transfer than a similar flow with the spent air leaving at the sides of the plate [9H].

Combined heat and mass transfer in porous media is important to such fields as drying, geothermal energy utilization, and heat transfer from underground buildings. A finite-element analysis [16H] has been found useful in studying applied heat and mass transfer in porous media including the influence of variable properties and composite porous media materials. Another study of coupled heat and mass flow in a composite medium shows the effect of the coupled flow on internal stresses [15H]. The influence of the Soret and Dufour effects on the diffusion of heat and moisture in solids has been analyzed [6H].

Simple models for combined heat and mass transfer have been applied to a laminar liquid film flowing down a vertical surface [14H]. Experiments show that the heat transfer over a flat plate may be augmented by a significant factor when mist flow is present due to evaporation of the water droplets [8H].

A "film penetration model" has been used to study convective heat and mass transfer between two phases [18H]

CHANGE OF PHASE

Boiling

Nucleate boiling. The influence of nucleation of one bubble on another during nucleate boiling was analyzed [57J] and photographs of the process were taken. Correlations for the onset of nucleate boiling were reviewed [41J], several of which were recommended. Boiling on a thin heated wire of pulsed current was investigated [104J] to study boiling with intermittent superheating.

A study of growth of bubbles on heated surfaces [134J] lead to an expression for the bubble breakoff diameter and departure frequency. The effect of hydrodynamics on the shape of vapor bubbles [108J] was analyzed. A model for the equilibrium radii of vapor bubbles and liquid droplets was devised [84J] using the Thomson–Helmholtz equation for vapor pressure on curved surfaces. It was concluded that, in many instances, the difference of pressure across the interface is significant. The conservation equations were solved [18J] to determine the rate of bubble growth on heated surfaces within a superheated liquid boundary layer. A correction to account for difference in refractive index of light in photographic studies of bubble growth was developed [143J]. With the correction, it appears that a bubble remains spherical from nucleation to breakoff.

Several studies dealt with boiling of non-standard fluids. The mass transfer of the liquid–vapor interface was evaluated analytically for two-phase multicomponent mixtures [112J]. The mechanisms of helium boiling were experimentally investigated [102J]. Helium flow boiling in tubes [2J], low pressure boiling of cryogenic liquids [98J], and film boiling of the super fluid Helium II [76J] were studied. Evaporation (thermal decomposition) of foams was studied [43J] experimentally using a 0.6% surfactant solution in tap water.

Enhanced heat transfer using a surface with pores and interconnecting tunnels was studied experimentally [91J] and analytically [92J]. It was found that with this surface/subsurface geometry, wall superheat could be reduced 80–90%. A review of structured-surface enhancement literature was made [132J]. A study on surface effects of prolonged boiling [52J] showed no support of the ageing theory.

Enhancement by vibration was studied on a horizontal wire [93J]. The wire was mechanically vibrated; an increase of heat transfer was observed at certain frequencies. Various enhancement techniques were tested on boiling of cryogenic fluids [99J]. The heat transfer coefficient was increased 8–10 times for nucleate boiling by covering the tube with wick material, and was increased 5 times for film boiling by introduction of internal fins.

Forced convection boiling. A mathematical model of dispersed annular forced-convection flow was developed [60J] by applying conservation equations for each region of the flow. A model for the variation of flow regime along a vapor-generating channel [73J] was presented. An analysis of laminar dispersed (mist) flow under constant heat flux and constant wall temperature boundary conditions [137J] was used for discussion of the fundamentals for this flow regime. Spectral analysis of the acoustic noise of boiling has been employed. Forced convection boiling experiments in an annulus [131J] revealed information about boiling modes, both in the spectra and in total intensity. The onset and development of harmonic, high-intensity pressure fluctuations in steam-generating channels was studied [100J] by spectral composition. Flow stability in commercial boiler tubes was experimentally studied using spectral analysis [113J]. Stochastic fluctuations of void fraction in a flow-boiling channel were studied using spectral analysis [55J]. The results lead to a model for propagation of vapor fraction perturbations. An analysis of subcooled low quality boiling at high pressures resulted in a model for prediction of void fraction [31J]. An experimental study was made with boiling at low pressures [58J]. Flow instability measurements in multi-channel boilers were taken [59J]. Flow pattern instabilities were observed. The effect of tangential conduction and non-uniform heat flux along the perimeter of a horizontal tube with saturated flow boiling was studied [14J].

Annular dispersed flow boiling in tubes with flowing sodium [142J] showed that phase change was by evaporation from the liquid film surface without vapor generation at the wall. Injection of inert gas or the presence of artificial cavities could be used to fix the point where the vapor phase appears. The effects of centrifugal acceleration and subcooling on nucleate boiling of cryogenic fluids (nitrogen and hydrogen) were evaluated [69J]. Acceleration was a high as $2000g$; the effects on the onset of nucleate boiling and on CHF were observed. Boiling Freon-113 (both forced convection and pool boiling) was experimentally studied in an upflow vertical tube to observe nucleate, transition and film boiling [140J]. CHF increased with the root of velocity and transition boiling was very sensitive to velocity. Experiment with refrigerants and refrigerant – oil mixtures showed the effect of oil carry-over on evaporator performance [22J].

Turbulence promoters were evaluated for boiling flow in an annulus [21J] with uniform and distributed heat flux. Internal spiral ribbon mixers were found to be more effective for single-phase heat transfer than for subcooled nucleate boiling [3J]. The evaluation used the parameter pumping power/heat transfer as a descriptor of performance.

A correlation of data for commercial heater tubes and common heat transfer fluids was presented [119J]. A survey of forced convection boiling correlations was presented [44J].

Droplet dispersed flow boiling between rod bundles during reactor emergency cooling conditions was analytically studied [136J]. There was an extra dependence of Nusselt number upon mean vapor temperature; it was concluded that pipe flow is a poor approximation to this complex geometry. A two fluid (liquid and vapor) model of two-phase flow as proposed for nuclear reactor studies [20J]. The conservation equations were written for the two fluids separately; they were matched at the phase boundaries.

An effect of electric field on forced convection boiling was found [12J] for field strengths greater than 1000 kV/m.

Forced convection critical heat flux in a vertical tube was studied under various conditions. General features of CHF in flows in vertical heated tubes with zero inlet subcooling were presented [62J]. A test of previous correlations against new data was made [63J] and appropriate dimensionless groups were recommended. CHF with reference to dryout, inlet subcooling, and boiling length was evaluated analytically [64J]. A high-pressure correlation ($0.1 < \rho_v/\rho_l < 0.3$) was recommended [65J]. Burnout under conditions of subcooled boiling and forced convection was discussed [87]. A generalized CHF correlation based upon 800 data points for flow in an internally heated annulus [118J] was given. Annular CHF data with (i) the rod heated and shroud unheated with (ii) with the rod unheated and shroud heated was correlated [66J]. CHF data in parallel flow between heated plates was taken and correlated [67J]. The effects of channel length and dissolved gases on CHF were evaluated; [68J] and [32J], respectively. A state-of-the-art review of the boiling crisis with respect to reactor safety was given [130J].

A study of CHF on a heated plate with an impinging water jet [87J] revealed different boiling regimes depending upon volumetric flow rate.

Evaporative heat transfer to dispersed flow was analyzed [71J] as a three-path problem; (i) wall-to-vapor, (ii) vapor-to-liquid and (iii) wall-to-liquid. It was concluded that the wall-to-vapor heat transfer was predominant. The minimum heat flux and lower-bound for droplet size in post-dryout dispersed flow was analytically evaluated [25J]. The predicted minimum drop sizes were smaller than observed in tests. A non-equilibrium model for dispersed flow based on heat transfer effectiveness between phases [115J] was developed to describe heat transfer and droplet diameter. In an experimental study of the same flow type, vapor superheat was measured [95J]. Details of the superheat probe design were presented. The effect of roughness in dispersed flow and annular dispersed flow was analytically evaluated [125J]. A perturbation technique applied to the hydrodynamic boundary layer in subcooled film boiling showed that shear stress at the phase interface influences the potential flow only slightly when the subcooling is large [29J]. When the core flow is near the saturation temperature, the other extreme, the inviscid solution does not describe the liquid motion; but, for the heat transfer problem, the liquid boundary layer and the vapor are decoupled. Visual observations in an annulus with and without obstacles on the heated wall showed that dry patches form upstream of the obstacle for slug and froth flows and downstream for annular flows [30J]. In an analysis of rewetting [116J], it was determined that the process of removal of a non-condensible absorbed gas layer from the surface was controlling.

Natural convection boiling. Basic studies in the mechanisms of natural convection (pool) boiling included one on the dynamics of growth and breakoff; behavior of the microlayer, and boiling in slotted channels [6J]. Another investigated the bubble departure radius under low gravity (1 g and below) conditions [23J]. It was found that the critical radius increases considerably under "microgravity" conditions in boiling CBr_4. A study of the mechanisms of boiling and evaporative cooling showed fluctuations of surface temperature in the vicinity of a single nucleation site of 6–10°C [120J]. The mechanisms of boiling on a horizontal plate or horizontal wire in helium were experimentally studied with an emphasis on rates of bubble growth, break-off diameter and departure frequencies [103J]. Motion pictures were taken. Holographic interferometry was employed in the investigation of the initial stage of nucleate boiling in a superheated boundary layer [51J]. An analysis of thermal stability of liquid droplets on a heated surface was made [46J] using small-perturbation methods. Droplet stability increased with bi- and hemispherical droplets were more stable than flat layers. Taylor instabilities in boiling, melting, condensation or evaporation were analyzed and investigated experimentally [127J]. The effects of viscosity, fluid layer height and surface tension on Taylor wavelengths were of concern. Contributions of various boiling mechanisms at subatmospheric pressures were assessed for a flat horizontal surface [167J] and for a horizontal tube [28J]. Heat transfer in a narrow vertical channel could be categorized into three modes [121J]: (i) natural convection without boiling, (ii) intermittent vapor generation, and (iii) vapor lock.

Experiments in pool boiling of mercury on a horizontal plate with an imposed magnetic field parallel to the direction of gravity [128J], showed that increased magnetic flux decreases both the incipient boiling and burn-out heat fluxes.

The effect of surface boiling on the process of material vaporization using high intensity irradiation was studied [17J]. An analytic study of boiling heat transfer on slotted surfaces [72J] lead to some recommended correlations. Boiling heat transfer and CHF were experimentally studied on flat plates with slotted, capillary and capillary-porous (wick) structures [1J]. A thin film if silicone was added to an upward-facing copper surface making it an ill-wetted surface for water [138J]. The behaviour of bubble growth was similar to that of film boiling on an ordinary (wettable) surface which is quite different than that of normal nucleate boiling. Sublimation of a horizontal slab of dry ice was presented as an analog to pool boiling on a flat plate [26J]. This study was presented as a model for the problem of reactor core (UO_2) melt. The effect of wall curvature on boiling heat transfer from a hot pool to a cold wall was experimentally evaluated [39J].

Augmentation of pool boiling by electrolytic generation of hydrogen gas was found to be effective for higher rates of heat transfer [90J]. A regression analysis applied to 5000 natural convection boiling data points [129J] resulted in several recommended correlations. The domain of fluid types was separated into water, cryogenic fluids and refrigerants.

Several effects on boiling heat transfer with sea water were studied (106J). Surfactants can increase the heat transfer coefficient by making bubbles smaller and departure frequency greater; a correlation for the effect of scale formation with sea water was presented. A fluidized bed condition was found to have enhanced boiling heat transfer from a horizontal cylinder [126J].

Critical heat flux data were found experimentally in a natural convection flow chaneled between two parallel, horizontal disks, where the lower surface was heated [61J].

An analytical model for the prediction of the minimum film boiling temperature [78J] was developed. The minimum film boiling heat flux from flat plates and spheres in saturated and subcooled liquids was found [45J] to be variable over a wide range, depending upon properties of the heater surface and boiling fluid.

Condensation

Several studies of the mechanisms of condensation were made. Approximations of the isotherms of superheated vapor were used to calculate the pressure in an embryonic droplet [139J]. The theory of non-equilibrium phase change and the advisability of using simple methods to calculate mass transfer were discussed [81J]. The latent heat release due to condensation, vapor phase removal and change of vapor structure were taken into account [109J]; at higher pressure, the critical radius of droplets is comparable to the mean free path. Transient surges in tube-type condensers were analyzed [10J, 11J]. Condensation of a vapor into fog at high temperature is radiatively induced [19J] and greatly enhanced heat transfer communication from the gas to a boundary. Heat transfer by film condensation in a binary mixture was analyzed [74J]. There is species diffusion of the more volatile away from the wall.

Film condensation. Heat transfer on a vertical surface with film condensation of a stationary vapor was evaluated [75J]. Laminar film condensation in the presence of waves was analyzed [123J]. Perturbation methods were applied to study nonlinear stability of a vertical condensation film [133J] leading to an expression for the wave amplification rate. An experiment was made [40J] to study the film breakdown and dry patch formation process. Dropwise condensation of steam in a vertical tube was studied [54J]. The effect of surface thermal conductivity on dropwise condensation was evaluated experimentally [124J]. Condensation curves of Q vs ΔT were essentially the same for copper, bronze and ptfe-coated surfaces. An analysis of the effect of droplet trajectory on heat transfer from cylinders having a liquid film boundary layer at the surface and a vapor outer layer was made [79J]. A set of equations was recommended for laminar film condensation of a binary miscible vapor [37J].

Forced convection condensation. Forced convection condensation on a horizontal tube was treated theoretically [33J] and experimentally [35J]. Forced convection condensation on horizontal flat plates and in horizontal tubes in the presence of a non-condensing gas was investigated [114J]. Film behavior at breakdown on the flat plate has similarities with open channel critical flow. Forced convection laminar filmwise condensation on a vertical tube was found to be characterized by five dimensionless parameters [27J]. Centrifugal acceleration was found to enhance film condensation heat transfer considerably [86J].

Condensing flows in porous media were studied. An analysis of flows similar to those in steam-injection secondary oil recovery was analyzed [97J]. A condensing wave, which has a saturation shock discontinuity, propagates into the dry, porous matrix. For small ΔT there is no local temperature change but there is a discontinuity in quality. A similar flow was studied experimentally using Freon, [96J]. The axial distribution of condensate was wavelike and had a saturation-jump at the leading edge.

Natural convection condensation. A study of flow patterns for condensation on the outside of horizontal tubes [15J] showed that a key parameter is the ratio of shear to gravity forces. Laminar filmwise condensation on a horizontal tube with circumferential grooves was modeled [34J]; the results were compared with experimental data. A similar analysis was made for finned tubes with convection on both sides of the tube wall [111J]. An analytical and experimental program on finned tubes found regions of high heat transfer coefficient in the trough of vertical finned tubes [48J]. The film in the trough was thin due to suction of the liquid flowing within the trough. It was suggested that fins and troughs be made thinner. An analysis of a vertical fluted surface was made [101J] by first analyzing the hydrodynamics of the isothermal flow, then including condensation of vapor to find an expression for the average Nusselt number. A study of condensate film flow in horizontal tube bundles [122J] showed that a reduction in spacing reduces weight of liquid films and a reduction of thermal resistance. Various enhancement techniques used in condensing steams were reviewed [82J]. Condensation of steam in contact with cold water (pertinent to LWR safety) was reviewed [5J]. Instabilities leading to large and rapid variations of heat transfer coefficient are poorly understood.

Free condensation. Equations describing the dynamics of vapor bubble collapse were developed and an expression for the heat transfer between phases [94J] was formulated. This vapor bubble model could be used to predict shock waves in liquids containing collapsing vapor bubbles. A similar analysis [38J] was made to determine the pressure wave produced by the collapse of a bubble. Direct contact condensation of vapor on a spray of subcooled liquid droplets was studied analytically and experimentally [77J]. The most important parameter was the initial drop size. A "universal" flow map was developed [13J] for direct contact condensation problems. Measurements were made in the condensation region of a steam jet submerged in water [4J].

Heat transfer studies in two-phase closed-type thermosyphons [9J, 53J] lead to correlations of heat transfer coefficient and optimum quantity of working fluid. Rates of thermocapillary convection were measured and compared with analysis [7J].

Vaporization

Vaporization of films. Liquid–vapor interaction and entrainment as found in falling-film evaporators were analytically studied [141J]. The tubes were horizontal and liquid entrainment was by stripping action of the crossflow. Stability of the falling film was experimentally evaluated [42J] leading to curves of minimum irrigation density versus heat flux. A mechanistic model for a liquid film draining down a heated wall countercurrent with its rising vapor [117J] showed that the liquid film downflow is limited by vapor upflow. The geometry simulated a PWR downcomer. A study of heat transfer to thin liquid films with low and high evaporation rates [135J] lead to some key parameters to the problem.

An analytical model for predicting moisture and temperature distribution in a moist, porous material during drying was developed [80J] which accounted for departure from thermodynamic equilibrium. A numerical study was made of evaporation of moisture on a plate maintained at a constant wet bulb temperature [89J]. A round, laminar hot-air jet impinging upon the surface effected the drying. Drying of a dielectric surface using radio frequency and microwave electromagnetic fields was studied [105J]. The process characteristics were determined by the power absorbed by the wet surface, pore structure of the surface and effective specific heats.

Free vaporization. Vaporization in free flashing liquid flows was studied. Flashing in flowing fluids is due to (i) static decompression and (ii) turbulent fluctuations [56J]. Spray flashing of superheated water was found to be faster than in a liquid jet or a suddenly depressurized pool [36J]. Experiments with isoenthalpic flashing of flowing water in pipes showed that the liquid temperature exceeded the vapor temperature [83J]. Comparisons were made between equilibrium and measured qualities.

Evaporation of free droplets in laminar tube flow at low pressures was studied [110J] under constant heat flux and constant wall temperature boundary conditions. A theoretical study of free droplet evaporation indicated that the process is unsteady and the droplet liquid is non-isothermal and is circulating [107J]. The effect of an ion wind on free surface evaporation into a laminar air stream was experimentally evaluated [47J]. Under laminar boundary layer conditions, the evaporation rate increased as the root of the current density. With high current density the boundary layer became turbulent and the evaporation rate became less sensitive to current density. Evaporation of a liquid drop on a hot liquid surface was experimentally studied [49J]. The evaporation time was comparable to that of the case of a droplet on a hot solid surface. The experiment allowed evaluation of liquid–liquid direct contact heat transfer. A similar experiment [50J] was used to identify twelve types of heat transfer modes. A numerical analysis of a droplet evaporating on a liquid surface [70J] showed that evaporation was limited by resistance to heat transfer within the droplet. A closed periodic condensation—evaporation cycle of a droplet (i) in a thermal gradient or (ii) between two stratified fluids, was analyzed [85J]. The droplet falls into a hotter, more dense liquid, vaporizes, then rises into the colder, less dense liquid and condenses, completing the cycle. Cinemicrophotography was used to study the boiling of water-in-oil emulsions [88J]. Two processes of bubble formation were found: (i) bubble formation on the solid surface and (ii) casual bubble formation away from the surface. The effects of sodium entrainment and heat transfer with two-phase UO_2 were studied [24J]. Taylor instabilities can cause entrainment of sodium coolant. The dominant heat transfer mechanism is radiation. The effect of heat transfer is to reduce fuel vapor pressure and reduce expansion work.

RADIATION

Radiation in participating media

Radiative transport in emitting, absorbing, and scattering media is of continuing interest. Exact solutions have been obtained for radiation heat transfer between parallel plates separated by an absorbing, emitting and Mie-anisotropically scattering medium [31K]. Using a differential approximation for analyzing an axially symmetric radiation field in a gray medium within a finite, cylindrical enclosure results in solutions which demonstrate that the accuracy of the differential approximation is of the same order for axially symmetric and one-dimensional problems [13K]. The radiative heat transfer problem for an isotropically scattering slab with specularly reflecting boundaries may be reduced to the solution of a set of algebraic equations by expanding the source function in Legendre polynominals in the space variable in the integral form of the equation of radiative transfer [19K]. A rigorous solution of radiative transfer in an absorbing and anisotropically scattering slab based on projectional methods results in computational formulae which can be numerically processed [23K]. There is a possibility for a unified presentation of experimental results obtained along isochores and isotherms and along the coexistence curves of CO_2 and Xe in the critical region, considering multiple scattering contributions to the depolarization of radiation [25K].

Neither narrow-band nor wide-band models are necessary to model non-homogeneous effects on radiative heat transfer in high temperature combustion gases. A simplified method based on total transmittance data reduces computational times over two orders of magnitude with a sacrifice in accuracy of less than 10% [11K]. A refined method for calculating the emissivities of individual components (H_2O, CO_2, CH_4) in the product gases of hydrocarbon combustion and of mixtures of these components indicates that this method can be employed for more complex calculations of the radiative energy transport [24K]. The efficient extraction of a high-temperature working fluid from a coal fired fluidized bed combustor depends on the design of the immersed heat exchanger, in particular, on the solidity of the cooling tubes immersed in the bed [16K]. There are certain similarities between the free vertical development of the vortex flame in a high power gas and oil flame in a cyclone furnace and the flame from bottom burners. The data obtained in this study can be used for the analysis of systems of boiler furnaces with bottom arrangement of gas and oil burners [17K]. Monte Carlo techniques for the stimulation of radiation in industrial furnaces can be conveniently used to compute the view factor matrix entering into Hottel's zone method [26K]. It is demonstrated that the introduction of an effective temperature is a useful tool for calculating radiative heat transfer in modern power plants [3K]. Studies of the heat transfer mechanisms in horizontal flame propagation indicate that in the early stages of a fire, heat conduction through the solid is dominant; radiation from the flame becomes of increasing importance as the size of the fire increases [21K]. Treating a flare as a surface radiator results in data which are close to the required accuracy for safety considerations [1K].

A collation method employing piecewise cubic splines as approximating functions and Gaussian points as the collation points provides a very convenient technique for the solution of thermally developing combined radiation–convection problems with and without scattering [7K]. Another collation method for the solution of linear and non-linear integral equations employs piecewise Hermite splines as approximating functions and the Gaussian quadrature points as the collation points. Since it is a high-order method, it requires only a small number of equations to produce the desired accuracy at low computational cost [9K]. Using the method of collation, results for thermally developing Poiseuille flow with scattering show that scattering tends to decrease the radiation component without affecting convection at low optical thicknesses [6K].

Studies of the coupled problem of radiative transport and turbulent natural convection in a volumetrically located, horizontal, gray fluid layer show that under severe radiation conditions, no boundary layer flow regime exists even at very high Rayleigh numbers [10K]. Studies of the effect of radiation in combination with turbulent natural convection on the rates of heat transfer in volumetrically heated fluid layers at relatively high temperatures demonstrate that even at high Rayleigh numbers the radiation mode is as effective as the turbulent natural convection mode in removing heat from the upper surface of molten pools with adiabatic lower boundary [8K]. An analysis of radiative energy transport in porous media reveals a convective-like radiative energy transport mechanism and it is suggested that this term is proportional to the void fraction gradient [30K]. A fluidized bed is utilized for checking the validity of the hypothesis that the various components in combined conduction, convection and radiation heat transfer are additive [20K]. Heat transfer by simultaneous conduction and radiation in an absorbing, emitting, and anisotropically scattering medium is analyzed by solving the integral–differential equations by a successive approximation technique. The results show that for a one-dimensional system, the common approach of treating the total heat transfer as a simple addition of separate independent contributions of conduction and radiation is in many cases very inaccurate [32K].

Expressions are developed for predicting the effect of volume and interface absorption and of scattering in high-reflectance or anti-reflectance multi-layer coatings. These expressions are used together with experimental data to predict the performance of quarter wave high reflectance and anti-reflectance multi-layer stacks at the design wavelength [2K]. By using a prism of high index of refraction as a substrate for depositing nearly transparent, thin layers, the index of refraction of these layers can be measured with high accuracy (to the third decimal place) [4K]. If an optically thick layer containing spherical pigments (TiO_2, Fe_2O_3) is painted on a specularly reflecting substrate, then the hemispherical reflectance will be affected by the absorption of the substrate (wavelength range from 0.35–20 μm) [14K]. An analysis of the heat transfer through irradiated layers of slag at high temperatures demonstrates that the treatment of slag as an opaque substance can result in large under-predictions of the total heat transfer in comparison to the situation where the material of the layer is semi-transparent to radiation [27K].

Studies of the thermal emission of a polydisperse aerosol medium indicate that ignoring the fog thermal emission can lead to large errors in the assessment of the performance of optical detection systems [29K]. The results of studies of the radiation properties for polydispersions of absorbing spherical particles may be applied to coal with wavelength dependent optical properties [5K]. Analytical and experimental results of studies of the visible radiation transfer in a black ink suspension are in good agreement for certain laboratory conditions [28K].

The conditions required for self-focusing of stationary Gaussian and circular high-power laser beams are derived for the case when radiation-induced heat generation contributes to temperature non-uniformities in the gas [22K]. Deflagration waves supported by thermal radiation may be classified as supercritical and subcritical deflagration. Subcritical deflagration leads to larger compression [18K]. Tables have been developed for radiative volume heating of spherical water droplets in black body surroundings up to 1450 K. From these tables one can find the time required to evaporate from one size droplet to another [12K]. Measurements of net heat losses to a clear sky as a function of surface temperature, ambient temperature, and humidity from both gray and spectrally selective surfaces are in good agreement with an analysis of sky-radiator-ambient heat exchange [15K].

Surface radiation

Results of a new calculation method of the local hemispherical effective emissivities along an isothermal, diffuse, cylindrical-inner-cone cavity demonstrate that this method provides high accuracy, especially for cavities with high surface emissivity, long cylinder length, and small aperture radius [14L]. The total hemispherical emissivity of a clean (100) surface of a single crystal tungsten over a temperature range from 340 to 1260 K is found to be only slightly sensitive to adsorption of mono-layers of oxygen on the surface [12L]. Measurements of the total normal emittance of AISI stainless steel samples oxidized at 1050 K show a remarkable influence on the surface finishing [6L].

An analysis of the angle factor between the inner halves of a cylinder which are assumed to be at different temperatures shows that the angle factor approaches $2/\pi$ as the aspect ratio (R/L) of the cylinder assumes values <0.01 [5L]. The shape factor between a differential plane area element and a three-dimensional object with straight edges can be expressed in terms of known shape factors using simple algebraic manipulation [13L]. Temperature calculations for shell enclosures under the influence of thermal radiation are rather complex due to non-linearity effects and the complicated view factors. Both difficulties can be circumvented through the use of upper and lower bound solutions which provide sufficient accuracy for determining thermal stresses in shell components [2L].

Measurements of the optical reflectivity spectrum of a $CuFeS_2$ single crystal at room temperature for a range between 0.025 to 6 eV allow the establishment of a schematic energy level diagram for $CuFeS_2$ [10L]. The results of an analysis of the reflectance of randomly rough surfaces show that the equations corresponding to the Fresnel approximation give the same results as those derived by means of the Fraunhofer approximation if certain geometrical conditions are valid which are determined in this study [11L].

By taking polarization effects into account, detailed numerical calculations of the radiative transfer for well known materials reveal up to 25% deviations from classical calculations [3L].

An adaptation of Kirchoff's and Draper's law for polarized radiation requires only two characteristic properties if radiative exchange is confined to smooth surfaces (no diffuse radiation) [1L]. A generalized temperature response chart has been developed for a body with negligible heat conduction resistance which is simultaneously under the influence of radiative/convective heat transfer in a medium with gray walls and a generally non-isothermal gas [7L]. An analysis of anisotropic conduction and surface radiation around a hollow cylinder is applied to a graphite-reinforced boom exposed to solar heating in space [4L].

Black fins attached to the base of the cavities of a V-groove cavity array promote both radiative heat transfer and collimation of energy in the direction normal to the base surface [9L]. Studies of the radiation properties of black chrome selective surfaces indicate their superior performance for solar collectors, especially when moderate operating temperatures are required [8L].

MHD

Renewed interest in MHD and its applications produced a relatively large number of papers during the past year.

It is shown that a set of two-dimensional turbulent boundary layer equations that describe the three-dimensional fluid flow in a MHD channel, fully satisfy the three-dimensional conservation laws [2M]. The effects of the Hall and the ion slip currents on forced convective heat transfer in the thermal entrance region of a MHD channel manifest themselves by a reduction of the heat transfer rates [3M]. A study of the effects of a transverse magnetic field on forced and free convection of an electrically conducting fluid flowing over a vertical semi-infinite plate indicates that a reverse flow of air exists near the plate when $Gr < 0$. In this study dissipative heat and stress work is taken into account [12M]. The study of thermally driven hydromagnetic convection in a rapidly rotating sphere may have possible applications to the Earth's fluid core where the work done by the buoyancy force may provide the necessary energy to drive the geodynamo [6M].

Viscous and Joule dissipation effects on MHD free convection flows past a semi-infinite vertical plate become more dominant with increasing values of the magnetic field parameter and the Prandtl number [14M]. A study of the combined buoyancy effects of thermal and mass diffusion on MHD natural convection flows reveals that for fixed Gr and Pr the value of X_t (dimensionless length parameter) decreases as the strength of the magnetic field increases [1M].

In order to reduce effects detrimental to the operation of a MHD power plant, a high ratio of volume of the MHD duct to its surface is required. The authors of this paper claim that efficiencies up to 60% are feasible in a conventional steam power plant equipped with a MHD topper [10M]. Studies of the operating region of MHD generators indicate that the optimal operating range for maximum electrical power output lies on the boundary between the transonic and supersonic flow regime at relatively low inlet stagnation pressures [15M]. In the development of a high-power prototype portable MHD generator system, a number of significant advances have been made, such as combustor heat release density, combustion efficiency, channel power density, and energy extraction rates [13M]. There is a possibility to produce short burst of power with electrolytes as the MHD medium because many electrolytes are soluble and ionized in water vapor above the critical point [9M].

A simplified version of the line using reversal technique is used for measuring the gas temperature and the potassium atom number density of MHD combustion systems [8M]. Experimental values of the electrostatic sheath thickness which develops over the cathode surface in a MHD combustion plasma seeded with K_2CO_3 are in qualitative agreement with analytical predictions for different seeding ratios and applied potentials between the electrodes [4M]. Studies of single-phase (Na) and two-phase (Na/N_2) MHD pipe flows show that the wall-voltage profiles of single-phase flows are symmetric with respect to the center of the applied magnetic field region; two-phase wall–voltage profiles are asymmetric because of the expansion of nitrogen along the length of the test section [5M].

By applying radial electric fields to a flow of a dielectric organic fluid passing through an annulus between a Cu tube and a concentric wire, it was found that for laminar flow the heat transfer rates to the outer wall increased in the thermally well developed region and the thermal development region was advanced [7M]. Stability conditions are derived for different thermal boundary conditions of an electrically conducting fluid layer subjected to volumetric heating and bounded between two rigid surfaces in the presence of a magnetic field [16M]. A liquid metal flowing within metal walls and exposed to a magnetic field is stirred thermoelectrically if the interfacial temperature is non-uniform [11M].

MEASUREMENT TECHNIQUES

Developments of measurement techniques and instrumentation related to heat transfer studies are described by a number of researchers. Primary areas of activity include temperature and heat flux measurements, laser–Doppler velocimetry, hot-wire anemometry and transport property measurements.

A comprehensive review of thermometry, which cites the contributions of eighty publications, is presented [17P]. The effect of heat leaks in platinum resistance thermometry is analyzed and an experimental method is proposed for estimating the magnitude of this effect [15P]. An effective thermal/vapor barrier for precision temperature baths has been made by floating on the liquid surface a pile of common packing material such as styrofoam pellets fused together by a solvent spray [16P]. A method which uses several thermocouples and the wire bridge technique of true temperature indication provides a means for measuring the temperature distribution in high-temperature furnaces that is independent of thermocouple calibration or inhomogeneity errors [24P]. A very simple, inexpensive procedure for installing thermocouples in i.r. spectroscopy or reaction cells is to insert fine thermocouple wires (0.13 mm dia.) through small holes (0.25 mm dia.) drilled in i.r. windows (NaCl, KCl, CsBr) 3.2 mm thick and seal the remaining opening with "Vacseal," a silicone resin [10P]. The recovery factor of a cylindrical thermocouple with plane frontal area in normal flow has been investigated [5P]. The frequency response of wires used as sensors for temperature fluctuation measurements has been experimentally investigated [22P]. In a subsequent paper, three different methods of measuring the frequency response are discussed and an explanation is proposed why there are great discrepancies in the time constants as determined by these methods [34P]. A procedure for measuring translational flame temperature utilizing the laser induced fluorescence spectrum of OH is demonstrated [6P]. A simple differential technique using a floating Langmuir probe and a hot probe has been used to obtain direct oscillographic display of electron temperature oscillation in a plasma [41P].

An optical thermometer has been constructed which is based on the fact that the time constant for fluorescent decay of the red R lines of Ruby is a monotonic function of temperature over a range of more than 200°C [42P]. Reflectance errors in i.r. thermography have been analyzed and corrections are provided for converting the apparent radiance temperature to actual surface temperature [37P]. A simple technique is presented for characterizing the non-linear responsivity of infrared detectors such as HgCdTe [45P].

Two companion papers [27P, 28P], describe the problems encountered in the measurements of radiant heat flux in large boiler furnaces that result from ash deposition and describe instruments that can accurately measure the fluxes. An instrument for the measurement of heat flux from a surface with uniform temperature was found to have an uncertainty of $\pm 2\%$ in the range of 420–1670 W/m^2 [19P]. The responses of heat flow transducers, used in the evaluation of convective body heat losses, have been investigated at hyperbaric environments [29P].

Several researchers report studies dealing with the theory and application of laser-Doppler velocimeters

(LDV) [39P]. A new LDV has been proposed where the waveform of the Doppler signal changes according to the direction of the velocity vector, thus making it possible to measure selectively a specified velocity vector. Based on this new LDV, simultaneous measurement of the falling velocity and size of large droplets has been achieved by employing LDV to selectively measure velocity and employing two laser beams intersecting at right angles in the center of the LDV sampling volume to measure size [38P]. The azimuthal and axial velocity of the source-sink flow in a rapidly rotating cylinder were measured by using the back scattered mode of an LDV [43P]. Simple optical methods that can substantially increase signal detectability in LDV involve rotating the laser polarization to amplitude-modulate exclusively the Doppler signal [21P]. The fundamental limitations imposed by photo-detection noise on the accuracy with which flow velocity can be determined in laser anemometry has been investigated [31P].

An apparatus has been built which combines laser–Doppler velocimetry and optical plethysmography for a rapid, multi-parameter characterization of blood flow in cutaneous tissues [47P]. A laser crossed-beam anemometer has been applied to the study of capillary blood flow [20P]. In a new method of remote wind sensing (dual-frequency Doppler–lidar) two optical beams of unlike frequency are superimposed in the sensed volume and velocity information is obtained from the difference in the Doppler shifts of light scattered from the two beams by aerosols moving with the air [11P]. A two-color, two-spot laser velocimeter system has been shown to be an effective instrument for measuring atmospheric wind speeds at ranges up to 150 m [3P]. A laser beam manifold, a device which transforms a single laser beam into several uniform parallel beams, and particle photography system has been developed for use in fluid velocity measurements [33P].

A comprehensive bibliography of thermal anemometry papers published in 1977 and 1978 is presented [13P]. Both qualitative and quantitative features of unsteady and turbulent flow fields can be examined using combined simultaneous flow visualization and hot-wire anemometry [12P]. The error in mean and r.m.s. temperature measurements in the outer part of a heated jet discharged into still air using two standard hot wire–cold wire arrangements were found to be about 16% and 46% respectively at the half-temperature radius [1P]. A method is presented for the correction of measured higher-order moments of hot wire velocity and cold wire temperature signals for the respective parasitic sensitivities to temperature and velocity fluctuations [35P].

An improved feedback-stabilized Michelson interferometer is proposed in which the effects of mechanical vibrations are reduced by using a two-laser light source [48P]. Shearing interferograms of refractive indices around a flame and of spouting gas are presented to demonstrate the use of a lateral shear interferometer which uses twin three-beam holograms, the first of which plays the role of a beam splitter and the second of which eliminates the effect of tilt [25P].

Two papers addressed the problem of measuring mass flow rate. The quasi-steady solution technique which has been widely used for transient turbine-meter analysis has been shown to be not generally valid for two-phase transients of practical concern and a suitable analytical model has been presented [18P]. Using the pulsation properties of gas bubbles, it is possible to measure acoustically the volumes of the gas bubbles and, hence, possible to measure very low gas flow rates (from 4 to 100 mm^3/s) [32P].

A new high sensitivity micromanometer is described where the downwards or upwards displacement of menisci under the action of a pressure differential in the U-tube arrangement is magnified by a factor of 10^4 or more [23P]. A glass membrane manometer, usable up to 820°C, has been devised which makes it possible to measure pressure contactlessly with a sensitivity of 0.01 mmHg [30P].

Development continues in the areas of transport property and transport coefficient measurements. The measurement of thermal conductivity of gases with a precision of the order of a few parts in a thousand using a transient hot wire technique requires corrections for the change in resistance per unit length of the wires produced by thermal expansion and the effect of adding a filter network to eliminate stray 60 Hz electric pulses [8P]. A steady state apparatus has been developed for measuring the thermal conductivity of cast materials by employing a novel thermal symmetry arrangement [46P]. The accuracy implications of the geometry of a guard heater used on a thermal conductivity measurement device has been investigated [4P]. An apparatus that is capable of measuring thermal diffusivity between 80 and 500 K using a modified Angström method is described [44P]. A diffusion cell has been used to measure the molecular diffusion coefficient of carbon monoxide in a carbon monoxide–nitrogen mixture through cigarette paper [9P]. A new method of correcting for intermolecular collisions in the measurements of Knudsen accommodation coefficients for energy, using a hot wire instrument, reduces the uncertainty in the measurements to a few percent or less [26P]. Calculations have been performed to estimate the feasibility of conducting plume transport and diffusion studies by creating a plume of fluorescent particles that are then interrogated by a lidar in both the fluorescent and elastically scattered modes [40P].

A specific measurement program was devised and taken to the Arctic, to determine some aspects of ice-pack transport [14P].

English translations of Russian papers dealing with the following topics appeared in "Measurement Techniques": An infrared scanning device for temperature measurement [2P], a device for calibrating thermometers in the range 78–350 K [36P], and a method of determining the angular dependence of emittance at high temperatures [7P].

HEAT TRANSFER APPLICATIONS

Heat exchangers and heat pipes

The mass transfer analogy with naphthalene sublimation was used [21Q] to obtain coefficients on in-line pin fin arrays. Conditions were developed after the fourth row and in-line arrays transferred more heat than staggered ones at equal pumping power and heat transfer area. Heat transfer rates on the shell side of shell-and-tube heat exchangers increase [4Q] with use of cross baffles. Means for the avoidance of leakage flow in bundled-tube heat exchangers were discussed [24Q]. The mass of convective fins with minimum mass differs little from the triangular fin [13Q]. A study on generalization of the methods of heat exchanger analysis from the year 1942 by London and Seban was now published [12Q] as a pioneer paper. The evaluation of compact heat exchangers regarding heat exchange rate and pumping power was discussed [11Q]. A calculation [7Q] for fully developed flow in a heat exchanger with superimposed velocity pulsations indicates that the interaction of velocity and temperature pulsations introduces a new term in the energy equation and produces thus higher heat transfer rates. A fast and accurate graphical method was published [20Q] for the design of air conditioning cooling coils in which sensible and latent heat is transferred. An approximate explicit equation with 10 sets of empirical coefficients [18Q] allows a rapid calculation of the mean temperature difference in air-cooled crossflow heat exchangers. An analysis [16Q] considers radiation effects on the performance of high temperature heat exchangers transferring energy between water vapor and carbon dioxide on one side and helium on the other side. An approximate analysis [10Q] of crossflow heat exchangers by the method of weighted residuals compares favorably with the finite-difference method. The optimal area allocation between two stages of a heat exchanger system was analyzed [1Q] with respect to interstage temperature and area. A thermodynamic approach [6Q] to the design of heat exchanger networks provides a listing of solutions with a minimum number of heat exchangers, heaters, and coolers. Experiments [5Q] were used to evaluate blocks of four cross flow elements to approximate cocurrent and countercurrent heat exchangers. Practical problems are discussed for process heat exchangers including fouling [22Q].

The trade between accuracy and time requirement was investigated [8Q] for finite difference methods to calculate the temperature changes in thermal regenerators. Variable time steps provided improvement. Refined closed methods were presented [23Q] for counterflow thermal regenerators.

NTU values predicted with the Ranz–Marshall correlations [17Q] agreed with experiments for atmospheric spray cooling systems. Local mean and bulk temperatures in the dispersed and continuous phases were measured [15Q] in a spray column by a computer-aided experiment. Local heat transfer coefficients could be obtained from the results. An analysis of heat transfer surface geometries for dry cooling towers [14Q] permits selection of the optimum geometry and in this way directs research towards better surfaces. Direct contact heat transfer to drops exposed to an intermittent electric field normal to the trajectory was studied experimentally [9Q] for water drops 3.9–5.9 mm in diameter rising in a silicone oil. The drops were found to elongate periodically in the direction of the field.

The characteristics of sintered powder wicks were measured in a study of the operating limits of a heat pipe [19Q]. A model developed to predict the maximum heat transfer rate agrees well with experiments. An analysis [3Q] was used to study axial and azimuthal dryout in gravity assisted heat pipes and discusses the methods to prevent both. The heat transfer and hydrodynamics of electrohydrodynamic heat pipes have been studied [2Q].

General

The heat release from reactor fuel elements for fast transients were calculated [23S] by series expansion of the equations. The stability of two-phase flow in vapor generators with parallel channels was analyzed [17S] by computer analysis.

The analysis [16S] of flow in an agitated horizontal thin film evaporator was compared with experimental results. A summary paper [21S] compared available relations for heat transfer in agitated vessels for multiphase systems. A model was developed [9S] for momentum and heat transfer in mixers with close-clearance agitators to obtain relations between the power number and Reynolds number. Experiments [8S] verified the analysis. Maximum heat transfer coefficients in an apparatus containing dispersed two-phase systems can be expressed [15S] as a function of Grashof number times Prandtl number. Equations were derived [4S] which correctly described the influence of the parameters on heat transfer in bubble column reactors. Pulsations caused by interrupting valves with 50–1000 cycles/min increase heat transfer to water flowing at $Re = 6600$ to 28,000 [10S].

Heat treatment using internal friction caused by ultrasonic waves produces materials with good mechanical properties [12S]. An analysis [13S] of polymer reaction molding was tested by experiments. A model for non-linear shear stress and thermal effects in elasto-hydrodynamic line contacts was derived [11S] in qualitative agreement with experimental data. Experiments were performed [18S] to correlate bulk body temperatures on point and line contacts. An analysis [7S] indicates that thermal effects in the film are dominant in describing lubrication of journal bearings in turbulent flow. Thermally induced whirl was found experimentally [14S] to exist whenever the lubricant inlet temperature is higher than that of the bearing surface in hydraulic journal bearings. The thermal behavior of the step thrust bearings was analyzed [22S].

A computer analysis [1S] modelled heat transfer to slab-shaped food products by passing cold air over the product which is wetted continuously by a spray of chilled water. Spray quenching in a ventilated-duct fire is modelled [6S] by considering heat transfer between a cold liquid spray, a hot gas, and the ignited duct wall.

A review [5S] considers methods to measure the thermal insulation properties of fabrics in the presence of circulating air. A quasi-steady approach is used [19S] for the thermal analysis of insulated structures in the ground with a melting or freezing zone. Buried pipes, infinite strips and circular disks are considered.

Good results have been obtained [3S] in measuring heat transfer in steam turbines by relating the time dependent temperatures measured just below the wall surface to the fluid temperature fluctuations. The increase of heat transfer in a spark ignition engine could be correlated [2S] with the arrival of the flame front at four positions on the cylinder head.

LOX-cooled thrust chamber technology is discussed in [20S]. The response of graphite epoxy sandwich panels to measure temperature transients was investigated [24S].

Solar energy

Topics of major interest among the heat-transfer related solar energy publications include: solar radiation, flat-plate and concentrating solar collectors, heat storage, and system performance. A review of collector and energy storage technology indicated that collector technology is commercially available to achieve delivery temperatures up to 175°F at averaged yearly efficiencies better than 30% in good solar climates [34T].

The amount of solar energy that is intercepted by surfaces of any orientation is estimated from a new model of the clear sky spacial distribution of solar radiation [31T]. A statistical procedure has been employed to develop correlations between the hourly global horizontal radiation and its diffuse component [10T]. A Lambert conformal projection of the sun's path and of shading obstacles, combined with an overlay of concentric circles, facilitates an expedient analysis of various solar collector sitings [14T].

A linearized model of the dynamic performance of a flat-plate solar collector is shown to be satisfactory in many respects [6T]. A combined experimental and analytical study of the transient response of thermosyphon solar collectors indicated that there are long time delays in the development of the flow in the collector but that these do not affect the energy collection [16T]. Thermal performance and sensitivity analyses were conducted for a variety of high temperature flat-plate collectors [28T]. Collectors can be analyzed in terms of the variables generally used in analyzing other types of heat exchangers [24T]. A flat-plate solar collector with an evacuated tubular cover is predicted to be less efficient than one with two flat covers which are not evacuated [3T]. Incorrect evaluation of the convective heat transfer coefficient on the outer surface of flat-plate collectors can lead to large errors in the predictions of useful energy collected [25T]. Based on measurements of wind speeds near flat-plate solar collectors, it was concluded that it is not valid to take a single wind speed measurement and expect this value to give an accurate indication of the average wind speed across the collector surface [19T]. The thermal contact conductance of aluminum/copper interfaces was measured in vacuo with and without high conductivity silicone grease between the metals [26T].

An analysis of the solar collection capabilities of a flat-plate solar collector with a flat mirror allows a determination of the optimal collector and mirror orientations for a variety of applications [13T]. The concentration ratios of a number of flat-plate/flat-mirror solar collector configurations with fixed and movable mirror panels were calculated [12T]. A cusp mirror—heat pipe evacuated tubular solar collector was found to be more efficient than conventional flat-plate solar collectors when operated at elevated temperatures [20T].

A generalized technique for the optical design of solar concentrators has been developed which considers limb darkening effects, collector placement error, concentrator optical errors and concentrator pointing errors [8T]. Information theory has been applied to the problem of solar radiation collection and it was found that the optimum solar concentrator corresponds to a perfect imaging system, i.e. one that images the entire sky on the absorber with no aberrations [22T]. A realistic class of collectors with maximal concentration, which can serve as a basis for design and optimality studies, has been defined [7T]. Statistical methods were used to predict the effects of tracking errors on the performance of point focusing solar collectors [9T]. It is shown that paraboloidal mirrors of short focal ratio and similar systems can have their flux concentration enhanced to near the thermodynamic limit by the addition of non-imaging compound elipitical concentrators [33T]. A new stepped spherical concentrator of short focal ratio is suitable for high temperature applications, and the cost/performance trade-off relationships of the design parameters can be approached through the optical simulation method presented in [2T].

There was an increase in the number of studies reported in which the problem of thermal storage was investigated. Good agreement was obtained between experimental and analytical studies of the performance of a rock-bed heat storage unit [23T]. A packed-bed thermal storage unit has been dynamically modelled using the procedure of calculating the output temperature as the sum of earlier input temperatures, each multiplied by a predetermined response factor [27T]. Four methods of reducing the mixing of the fluid in a storage tank have been examined critically with a view toward updating the effectiveness of each [29T]. A two-tank heat storage system, which provides a method of positive antiblending using a flexible diaphragm to separate supply and return water in each tank has been designed [30T]. A method for the determination of the optimum economic distribution of thermal insulation on inground annual heat storage tanks is described [32T]. Heat loss and storage functions are derived for a thermal well [18T]. In an investigation of nitrate salts for latent heat storage, a method of estimating the thermal conductivity of the mixture is described and the experimentally determined temperature history of the storage material is found to be in reasonably good agreement with numerical predictions [11T].

A variety of systems were investigated. A number of ASHRAE calculation procedures have been combined to develop a method for predicting the performance of solar energized systems for the heating or cooling of buildings [17T]. The National Bureau of Standards fabricated, instrumented and tested six typical solar hot water heating systems and compared the experimental results to predictions performed using three different computer programs [15T].

A mathematical correlation between collector area and auxiliary energy used in a solar hot water system was obtained using a numerical transient system analysis program [5T]. Solar assisted heat pumps should have capacity modulation in order to achieve optimum performance [4T]. The heat and mass transfer analysis of grain drying for a prototype system is described and the results of a survey showing the effects of various system parameters on drying time are presented [21T]. It was predicted that the operation of solar ponds in the southern part of Iran is not affected greatly by the normal daily and weekly changes of climatic conditions [1T].

PLASMA HEAT TRANSFER

There seems to be an increasing interest in basic studies as well as in applications of ionized gases and in the associated heat transfer aspect.

The results of a simplified analysis of the arc behavior in SF_6 Puffer Breakers are in good agreement with measurements and permit not only the design for optimum performance, but also an estimate of the thermal behavior of the arc as current zero is approached [21U]. An experimental investigation of the arc phenomena in SF_6 Puffer Breakers shows that the arc column remains stable on the center axis during the high-current period and becomes turbulent near current zero [19U]. Modelling results of circuit interruption arcs in SF_6 taking axial inhomogeneities into account are in agreement with the results of full-scale interruption tests [4U]. Results of a new optical method for measuring temperature and pressure profiles in a transient arc generated by separating Cu/W electrodes are in good agreement with electrical measurements [25U]. The good agreement between analysis and experiment allows the application of sealing laws to gas-blast circuit breaker arcs during the high current phase [11U]. Possibilities are delineated of using the additional energy absorption capacity of magnetic-blast chutes for arc circuit interruption by increasing the permissible temperature of their walls up to the boiling point [33U].

Studies of the free recovery of wall-stabilized arcs with superimposed laminar or turbulent flows (axial) indicate that the conductance decay rate increases with mass flow rate. This and other findings are explained in terms of a boundary layer arc model which includes turbulent diffusion effects [15U]. Analytical investigations of the free recovery of the gas blast arc column show that the temperature decay of the arc column in N_2 is much faster than in SF_6 [27U]. The thermal interruption capability of an arc in a double flow configuration is drastically reduced by the vortex superimposed to the axial flow [31U].

The results of interferometric and shadowgraph investigations of arc–flow interactions in a double-nozzle flow system allow for the first time a sharp distinction between different forms of arc–gas flow interactions [32U]. Analytical results of the response of a wall-stabilized air arc to step and sinusoidal current changes are in good agreement with experimental findings [23U]. An experimental study of non-equilibrium effects in wall-stabilized argon arcs indicates that the electrons are not in equilibrium with the heavy particles at low currents and low pressures [30U].

Temperatures in SF_6 arcs covering a range from 9000 to 20,000 K may be derived from a combination of measured SI, SII, FI, and FII absolute line intensities and computed equilibrium plasma composition data using an iterative procedure [29U]. Results of temperature measurements in turbulent arcs indicate relatively large fluctuations in temperature ($\approx 5\%$) across the entire arc column [8U]. A new spectroscopic method useful for temperature measurements in thermal air plasma is based on measurements of the integrated emission coefficients of 19 rotational lines concentrated around the band head at 391.5 nm (N_2^+ molecule) [28U]. Based on calculations of the index of refraction in a high pressure hydrogen plasma it should be possible by interferometric measurements to determine the electron density in a high pressure hydrogen arc with an accuracy of the order of 1% [26U].

A pulsed probe method may be useful for plasma flow boundary layer studies when physical conditions eliminate the possibility of using optical methods, and in some cases it may serve as a routine method for measuring free stream flow velocities of a plasma [12U]. A study of the effects of probe temperature and probe material on electrostatic probe measurements in a partially ionized, high density plasma shows that the ion current increases as the probe temperature increases and the floating potential shifts to more negative potentials [24U].

The electron density and the collision frequency in an over dense plasma cylinder produced inside capillary tubes may be determined by a two-frequency method measuring the reflection coefficient in a rectangular wave guide crossed by the plasma [35U]. A new method for atom temperature measurements in plasmas makes use of the thermal diffusion effect. For this purpose a light tracer gas is added to the plasma [13U].

The effects of cold gas injection on a confined arc column manifest themselves by an arc constriction at the location of gas injection raising the arc core temperature and resulting in additional resistance to the penetration of the cold flow into the arc [6U]. Considering the effect of convection on the stability of a two-dimensional arc, the results conform with those given by the classical Kaufmann criterion [9U]. The results of an empirically based model for a long, vertical d.c. arc in atmospheric air indicate a quasi-steady state between 20 and 5000 A and two distinct core temperature ranges around 7000 K and 12,000 K [22U].

A model for short arc thermal reignition indicates that this reignition takes place in a thermal layer near the anode [20U]. Modelling of the anode contraction region of an atmospheric pressure nitrogen arc at 250 A indicates that heat transfer close to the anode is dominated by electron enthalpy transport [7U]. The anode assumes different operating modes in a MPD arc configuration at low pressures (≈ 1 Torr) depending upon the parameter $I^2/\dot{m}$ (I = current, $\dot{m}$ = mass flow rate) [16U]. Considerable advances have been made in recent years in the understanding of the basic processes involved in the erosion of metal cathodes in electric arcs [14U].

Small additions of Cu-vapor to an atmospheric pressure nitrogen plasma produce a significant increase of the electrical conductivity for temperatures between 5000 and 7000 K [1U]. Both the thermal conductivities and the coefficients of thermal diffusion for a high temperature plasma in a uniform magnetic field have been calculated from an expansion in terms of Sonine's polynominals using 50 terms. The resulting accuracy extends to at least six decimal places for various magnetic field strengths [18U].

The percentage of ionization in a duoplasmatron in He reaches values up to 95% at 0.2 to 0.3 Torr and decreases to 15% when the pressure exceeds 0.5 Torr [10U]. A new approach for the ignition of pulverized coal makes use of a vortex-stabilized electric arc heater which saves substantial amounts of premium fuel. The arc igniter appears to be economically viable and competitive with conventional practice [2U]. Natural convection has a negligible effect on the flow and temperature fields of a confined, inductively coupled, thermal r.f. plasma, but a significant effect on a free r.f. discharge [5U].

For studying the heat and momentum transfer for alumina particles injected into a plasma jet, results are used derived from emission spectroscopy, laser–Doppler anemometry, and in-flight radiation pyrometry [34U]. Mixing of an argon plasma jet with the surrounding air is studied by using conventional techniques and a novel form of laser Schlieren velocimetry. Results indicate that there is a gradual degradation of non-translational arc energy in the innermost zone while the flow in the outer zone appears to be independent of events within the nozzle [17U]. The efficiency of a conventional plasma torch operated with argon at atmospheric pressure is typically in the range of 40–50%. By adding a small concentration of a diatomic gas, the efficiency increases to approximately 65% and, at the same time, the power dissipation in the torch increases [3U].

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