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HEAT TRANSFER—A REVIEW OF THE 1982 LITERATURE

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INTRODUCTION

THIS review surveys papers that have been published in the open literature covering various fields of heat transfer during 1982. As in the past, the number of papers published during that period was such that a selection only could be included.

A number of conferences dealing with heat transfer or including in their sessions some on heat transfer have been held during 1982.

The 24th Israel Annual Conference on Aviation and Astronautics held on 17 and 18 February 1982 at Tel-Aviv, included in its program papers on turbulence models to predict heat transfer and on film cooling of turbine blades. The papers will appear in the *Israel Journal of Technology*.

The 27th International Gas Turbine Conference and Exhibit held on 18–22 April 1982 in London, U.K., had sessions on external and internal blade heat transfer, on gas turbine waste heat recovery, on ceramic coatings for gas turbines, on film and on transpiration cooling. Copies of the ASME papers may be obtained by writing to the ASME Order Department.

The 3rd Joint AIAA/ASME Thermophysics, Fluids, Plasma, and Heat Transfer Conference, held on 7–11 June, in St. Louis, Missouri, devoted sessions to numerical heat transfer techniques, radiative heat transfer, thermal storage heat transfer, high temperature/high heat flux heat transfer, convective mass transfer, and to heat transfer in boundary layers. Papers are available at AIAA and ASME Headquarters.

The 17th Intersociety Energy Conversion Engineering Conference, held on 8–12 August, in Los Angeles, California, covered solar collector components, solar heating and cooling, and thermal energy storage in three sessions.

The big event of the year was the 7th International Heat Transfer Conference held during 6–10 September at the Technical University, Munich, Federal Republic of Germany. Welcoming addresses by representatives of the Assembly of International Heat Transfer Conferences, of the Bavarian government, and of the Technical University as well as an address by E. R. G. Eckert on "A Pioneering Era in Convective Heat Transfer Research", opened the conference. Technical sessions on all aspects of heat transfer were devoted to the presentation and discussion of more than 450 papers. Twenty-one keynote papers provided a detailed review of the present state of knowledge in flow boiling, heat transfer in turbulent flows, boiling of mixtures, numerical methods and visualization of heat transfer, radiative heat transfer, advances in compact heat exchanger technology, prediction of transport properties, boundary layer theory, forced convection heat transfer, particle heat transfer, heat transfer in combustion chambers, mass transfer in rheological systems, heat and mass transfer in rivers, cryogenic heat transfer, buoyancy effects in forced channel flow, natural convection in cavities and cells, heat transfer in the atmosphere, nuclear safety heat transfer, and heat transfer enhancement. The Max Jakob Award was presented to Chang-Lin Tien during the conference. The number of papers covered during the conference was such that they could not be included in the survey. They are, however, available as bound volumes in the *Proceedings—Heat Transfer 1982—München* from Hemisphere, Washington, D.C.

The 1982 Symposium of the International Centre for Heat and Mass Transfer, 30 August–3 September 1982 had as its topic heat and mass transfer in rotating machinery with ten invited lectures and 61 papers. The Proceedings of the Symposium are available from Hemisphere, Washington, DC.

The ASME 103rd Winter Annual Meeting, held on 14–19 November at Phoenix, Arizona, included in its program 19 sessions on various aspects of heat transfer including combustion-sprays, coal combustion, ice formation and arctic heat transfer, interaction of water chemistry and heat transfer in boilers and evaporators. The Heat Transfer Memorial Award was presented to Yasuo Mori of the Tokyo Institute of Technology, Tokyo, Japan. Preprints of the papers are available at ASME Headquarters and many of the papers will also be published in the *Journal of Heat Transfer*.

A number of short courses were organized during 1982, among them a lecture series on Film Cooling and Turbine Blade Heat Transfer, held on 22–26 February at the Von Karman Institute for Fluid Dynamics, Belgium. Short courses on Computational Fluid Mechanics and Heat Transfer were held at the University of Minnesota and at the Pennsylvania State University, and a short course on Measurement of Building Fire Safety was held at the University of Wisconsin.

A considerable number of books dealing with heat transfer or including heat transfer topics have appeared on the market in 1982. They are listed in the bibliographic portion of this review. Of special interest to engineers will be the *Heat Exchanger Design*

Handbook published at the beginning of 1983 by Hemisphere, Washington, DC. Volumes with the titles: heat exchanger theory, fluid mechanics and heat transfer, thermal and hydraulic design of heat exchangers, mechanical design of heat exchangers, and physical properties collect up-to-date information conveniently in five volumes. The *International Journal of Heat and Fluid Flow* resumed its quarterly publication in March, 1982.

The following highlights characterize the activity in heat transfer research in 1982.

Nearly half of the papers considering heat conduction were concerned with the presence of phase change. Some studies approached the problem analytically seeking verification of the models by comparison with suitable experimental data. Others report the results of experiments for specific systems. Many papers appear to have been prompted by a concern with actual heat transfer problems like freezing or thawing of soils, metal casting, or thermal oil recovery.

Channel flow papers dealt with uncommon property effects like non-Newtonian and low Prandtl number fluids, strongly available of properties and freezing. Turbulent flow studies included effects of flow separation.

Forced and natural flow and heat transfer were studied in saturated and unsaturated porous media and in fluidized beds. Attention in natural convection centered on heat transfer in horizontal layers heated from below or steady laminar or turbulent convection for constant and variable property fluids. Considerable interest is still shown in film cooling heat transfer.

The fundamental aspects of boiling heat transfer still need clarification. Studies in this direction covered nucleation at artificially produced sites, bubble growth, stability of film boiling and details of transition boiling. Papers dealing with applications centered on critical heat flux and post-CHF heat transfer or augmentation of evaporative heat transfer to strongly wetting refrigerants by use of finned tubes or tubes with porous coatings. Evaporation rates of liquid droplets in direct contact heat exchangers, in mist flows, and in electric fields as well as boiling in porous media have been examined.

Condensation has now become a sufficiently large topic to be treated separately with many of the papers dealing with the application to heat exchangers. Other papers correlated heat transfer behavior in liquid films with the state of the film. As a new topic, the collapse of a submerged vapor sheet in a sub-cooled liquid pool was investigated.

There is considerable interest in radiative transport in emitting, absorbing, and scattering media including surface effects.

Heat exchanger studies concentrated on augmentation by special surface shapes and flow arrangements as well as on optimization of complex heat exchanger systems. There were only a few papers on heat pipes. Heat transfer in new energy devices, in conservation, in computers, and in bioengineering is covered in the literature. Papers concerned with solar energy dealt with measurement and prediction of the availability of solar radiation, with the performance of flat plate solar collectors, and with heat transfer in thermal energy storage systems. Interest has been shown in plasma heat transfer connected with arc technology and with thermal plasma processing.

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

CONDUCTION

There continues to be considerable interest in specialized problems in heat conduction, particularly when the phenomena are accompanied by a change of phase.

Heat conduction from buried sources is analyzed for a fluid flowing in a pipe [4A] and for a sphere [3A]. For the pipe there are two cases: (1) involves mixed (convective) boundary condition with a uniform heat transfer coefficient at the pipe surface; and (2) laminar flow with linear temperature variation along the pipe, which couples the internal and external heat transfer processes, requiring simultaneous solutions of the energy equations for the two regions. The complicated geometry is handled neatly using the bicylindrical coordinate system, resulting in temperature distributions and shape factors in each case. The same coordinate system leads to an exact analytical solution for the steady-state temperature distribution in and around a heat generating sphere buried in a semi-infinite solid with an isothermal surface. The form factor and heat flux distribution along the medium surface are also reported and compared with an approximate source-sink solution.

At low pressures, consideration is given to the transition regime between hydrodynamic and Knudsen flow [18A]. Heat conduction through a diatomic, diamagnetic gas between parallel plates is represented by a simple model and explicit expansions found for the effect of a magnetic field. For the same parallel plate geometry, ref. [23A] considers the influence of accommodation coefficients and Maxwellian diffuse/specular reflection boundary conditions on the heat transferred through a rarefied gas, yielding results which agree within 3%.

Mathematical aspects of the conduction phenomena are the subject of a number of papers. Thus, ref. [35A] solves a non-self adjoint problem by an expansion in terms of the root vectors of the conduction operator and its adjoint using their orthogonality properties. Given a homogeneous isotropic elastic solid with memory, ref. [22A] treats the problem of time-dependent heat transfer by wave propagation due to the communication, at finite speed, that energy is being generated from a heat, chemical, or nuclear source. Effect of the wave is said to be noticeable in those practical situations characterized by short time and high heat flux. Noting the similarities between the vibrating string and certain heat conduction problems, ref. [34A] presents inequalities related to the norms of the solutions to the vibrating string and heat conduction partial differential equations; a maximum principle is shown to hold for both problems.

When two metallic surfaces are in contact, the question is raised about the heat transfer through the interstitial gas between the surfaces. The thermal conductance is measured in ref. [28A] by interpreting the phase data obtained by varying the laser source modulation frequency; experimental results confirm the hypothesis implicit in most theoretical formulations of the photoacoustic effect: that the surface resistance (thermal) is generally negligible.

A number of papers examine the stress in materials caused by thermal conditions. In solving the transient thermal stress problem for a hollow sphere under partial heating, ref. [56A] asserts that precise analysis requires that the corrected heat equation take into account the thermo-mechanical coupling term. The simultaneous solutions for stress and temperature distributions using a new numerical technique show a small lag in the case of certain materials. For an infinite, isotropic solid containing an annular crack, ref. [21A] seeks the axisymmetric thermal stress distribution; the problem reduces to triple integral equations, ultimately reduced to an infinite set of simultaneous equations. The relation between weak shocks and stress in heat conducting, thermoelastic materials is investigated using equations governing the growth and decay of wave amplitude obtained for shock waves of arbitrary form in a linear thermoelastic body [58A]. The stress 'jump' relation to shock strength is studied for second-order material.

For a spherical droplet moving into an unbounded volume of another immiscible liquid in creeping flow ($Re \ll 1$) the unsteady heat conduction is studied, with a result that an earlier solution to the problem is found to be unstable [16A]. Additional studies also find the techniques of analysis applied to problems emerging from technical practice. Thus ref. [26A] treats the problem of heat transfer from an elliptical cylinder moving through an infinite plate applied to electric beam welding. A general solution, in elliptical coordinates, is found for the two-dimensional steady-state temperature field from which the heat flux around the cylinder is determined, and the total heat flow rates found. The results are applied to evaluate the effectiveness of full penetration electron beam welding and to predict the relation between penetration depth and required power. In ref. [60A] heat transfer from wavy and straight wires of equal length are compared for surface temperatures maintained constant by forced convection. For non-uniformly heated wires, undulations in the wavy wire cause an increase in the total heat transfer, compared to the straight wire of the same length. In a nuclear reactor channel, ref. [20A] applies a finite-difference method to calculate heat transfer. The differential equations characterizing the separate system parts are connected by energy considerations involving fuel and cladding temperature. The method may be extended to other systems.

Several papers are concerned with heat conduction and chemical effects. Gaseous thermal explosion is treated in ref. [11A] where approximate solutions of the Arrhenius equation are evaluated. With general boundary conditions, critical ignition parameters are calculated in the case of finite Biot number. The rate of charring of a heated, one-dimensional wood-like slab is predicted in ref. [17A] by solving the transient conduction equation in the presence of a phase-change energy sink term. Rate and depth of charring are predicted for various boundary conditions and compared with experimental data. The sudden Joule heating of a system is used for studying chemical rate processes. Such an application at high pressure (2 kbar) is used to study fast reactions and verified by means of a well-studied reaction [8A]. In another instance, the same scheme is used to study chemical reaction kinetics in thin samples of electrically nonconducting systems [27A].

The resistance to heat conduction between surfaces in contact is the object of study for a number of papers. With roughness described by a stochastically varying local contact resistance, in a two-part study, general variational principles are derived, permitting the determination of lower and upper bounds of the macroscopic contact resistance [5A, 6A]. The method is illustrated by calculating an upper bound for a random arrangement of circular contact spots of equal size. The second work uses the method to determine upper bounds for arbitrary geometry and distribution of contact spots. Special attention is paid to a binary model which admits only two discrete values for the local contact resistance, inside and outside the direct contact areas. Again for two solids in contact, the thermal resistance is analyzed using as a model, a single heated channel of cylindrical contour and varying radius. The contact resistance of the interface is expressed as a function of the channel properties and extended to surfaces on the basis of materials used, number of contact areas, and a single geometrical property of the channel [47A]. The calculation of multilayer heat transfer is accomplished by a successive method which permits radiant heat exchange between interior surfaces to be considered if needed, giving results which compare favorably with field data [59A]. Turning to specific problems, ref. [51A] describes a procedure for predicting the recommended insert thickness which will result in minimizing the thermal resistance of a pressed contact between flat, non-wavy surfaces. The analysis is based on the assumption of ideal plastic deformations at interfaces between randomly high rough surfaces and insert material. Experimental measurements for several systems and theoretical predictions are in good agreement. For cladded fuels, the thermal gap conductance is studied by applying Kalman filter methods to an in-pile liquid metal fast breeder reactor simulation experiment [24A]. Interfacial resistance to mass transfer for dilute solutions is determined from the interfacial energy profile. Large resistance values appear to correspond to two energy maxima at the interface. The rate constant formulation used, in certain limiting cases, yields the same form as obtained by assuming local equilibrium directly across the interface [46A].

Heat conduction with finned surfaces features an investigation of two-dimensional heat conduction in heat exchanger fins since the difference between one- and two-dimensional analysis can be substantial. The complete assembly is considered, including supports, and the method is held to involve the solution of fewer equations than finite-difference or finite-element methods and yield accurate results for problems where these two approaches do not [13A]. The simultaneous solutions of heat conduction for the fin and convective heat transfer for flowing liquid obviates the need to use literature values of the convective heat transfer coefficient, customarily taken as uniform over the fin surface when the actual flow and boundary conditions are different from those in the literature [54A].

Heat transfer in the presence of a phase change is studied from various aspects reflecting a wide-spread interest in understanding the phenomena and the variety of its occurrence. The melting of a horizontal solid surface by an overlying hot, liquid pool is studied experimentally for several pool–solid substrate pairs [9A]. The influence of density differences, melt-layer viscosity and latent heats are examined and the results compared with theory. For a spherical enclosure containing saturated material, the enclosure temperature is suddenly raised. The flow field resulting from density differences between solid and liquid phases is observed to concur with that predicted analytically. The energy storage characteristics of an enclosure are studied [29A]. In a vertical tube, the melting of a medium changing phase is studied experimentally. In contrast with the numerical solutions, which use a pure conduction model, this study shows that convective effects can lead to energy transfers 50% higher [53A]. The importance of convective effects during a phase change is also apparent in the system consisting of a heated horizontal circular cylinder embedded in a phase change material. Using a numerical mapping technique to handle the moving boundary, results indicate that natural convection is important in all cases [37A]. For a melting, or subliming, flat surface in direct contact with a hot fluid, free convection again occurs as an important consideration [2A]. Water film cooling of surfaces is an established practice. A new correlation for predicting quench front velocity in rewetting of hot, dry surfaces by falling water films is derived and proves accurate to within 2.5% compared to the accurate numerical solution [33A].

The phenomena of solidification attract wide interest. In a two-part study, the mathematical analysis of the steady, dendritic solidification of an aqueous solution is first developed to yield families of temperature, concentration, and dendrite shaped profiles in two zones, near the basal plane and near the dendrite tips [31A, 32A]. This allows heat and mass transfer processes to be analyzed near the basal plane, then near the tips of steadily advancing dendrites. Geometrical and thermal criteria are used to insure that the fields for the two zones match. Using pure water cooled by a surface, ref. [41A] studies experimentally the initiation and spread of ice formation. Observed thicknesses are in good agreement with the approximate quasi-steady-state solution. In a rectangular enclosure with isothermal sides and adiabatic top and bottom surfaces, the process of solidification is analyzed. Convective effects are considered as well as heat conduction through the solid and the idealized mold. Results give velocity profiles in the melt, temperature distributions in the melt, solid, and mold [36A]. The solidification process on a small scale is studied by considering the thermal evolution of liquid and solid deposited during the solidification of spherical droplets of liquid. The system geometry becomes a hollow sphere because of the density difference between the phases [14A].

For the laminar flow of a liquid in a circular tube whose external surface is convectively cooled, ref. [40A] examines analytically the factors which influence the length of the freeze-free zone and the freeze layer thickness as a function of time and tube length. One-dimensional, transient solidification with super-cooling is studied analytically and experimentally. Observations enable phase regions to be distinguished and classified; the numerical method proposed yields results in good agreement with experiment for the single substance studied [42A].

For a warm, flowing liquid planar solidification is examined under different boundary conditions. The formulation leads to a coupled set of two differential equations in temperature and solid thickness as functions of time, position and problem parameters.

The results (temperature distributions in solid layer, solidification rate and time) agree with experimental results [43A].

The Stefan problem attracts the interest of several investigators. Considering the physical, mathematical, and numerical experience with problems of this kind, ref. [49A] advocates enthalpy (not temperature) as the desirable dependent variable. Discussion centers on the physical interpretation of the multi-valued function arising from the mathematical formulation. A one-dimensional problem, semi-infinite strip, with convective boundary conditions is considered; surface temperature, asymptotic behavior as the convective heat transfer coefficient grows large, uniqueness bounds on the phase change front and total system energy are discussed [52A]. In the Neumann solution of the two-phase Stefan problem, ref. [57A] examines the effect of replacing the coefficient in the free boundary condition by an inequality.

For solidification where conduction dominates and small temperature differences exist, ref. [48A] finds quasi-steady models an advantage. Shape factors are used to predict freezing rates and heat transfer, in various two-dimensional systems, from simpler equations. The method is not advised for determining local heat flux or details of interface shape.

Using a numerically based model, ref. [15A] developed a single analog to represent the one-dimensional heat transfer equation, with and without phase change. Accurate solutions are obtained for test problems using a small (hand-held, programmable) calculator.

The shape of steady-state solidification interfaces formed when liquid above the freezing point circulates over a cold surface is given by ref. [45A]. The surface shape is related to the crystal structures formed during solidification, a matter of concern in casting, the development of naturally strengthened metallic composites, phase change and energy storage devices. A related paper analyzes the solidification interface shape resulting from applied, sinusoidal heating, particularly in the light of metal casting process requirements [44A].

Heat transfer in the liquid zone which precedes the advancing condensation in an oil reservoir undergoing a thermal recovery process is taken up in ref. [61A]. Various analytical expressions for the temperature distribution in the hot liquid zone are derived for high and low injection rates.

The freezing and thawing of soils in the presence of seepage flow is analyzed by means of a system of computer programs based on the finite-element method [10A]. The simultaneous solution for the coupled velocity and temperature fields, made possible by assumptions held to be reasonable, yields results which agree with the laboratory model of the system. For vertical cylinders in free convection, ref. [7A] measures the frost growth. Heat transfer correlation is found to be effective in predicting frost growth rates.

Other problems involving heat transfer with phase change range from a consideration of the thermal stresses developed during solidification due to the transient temperature distribution stresses which depend upon the Stefan number, to the investigation of the factors which influence the solidification process in systems of heterogeneous particles [39A]. The results find application in establishing the conditions for minimizing the frozen regions in moist coal loads during winter rail transport [38A].

Papers on thermal conductivity of materials and systems include measurements, calculation of effective values, and thermal conductivity of special systems. The transient hot-wire method for measuring the thermal conductivity of orthogonal, anisotropic materials is first theoretically investigated, then applied to samples of such materials. The results compare to within 5% of those obtained by the traditional one-dimensional steady-state method [55A]. A new, transient hot-strip method is examined theoretically and points to the need to include second-order terms for the hot-strip electrical resistivity dependence upon temperature [12A]. Considering a 'sphere-pac' nuclear fuel assembly, ref. [1A] reports a two-dimensional finite-difference method for calculating the effective thermal conductivity which gives results within $\pm 20\%$ of experimental values. For wet, fibrous sheets, hot-wire measurements at various moisture content, void fraction, and temperature values provide a basis for a porous structure model for wet fibers and the calculation of effective thermal conductivity for such a medium [19A]. Using five pulverized-coal samples, ref. [25A] applies a modified hot-wire method, and the principle or differentiation thermal analysis, to measure the effective thermal conduction of such systems from room temperature to 850°C. For three general types of soils, ref. [30A] calculates their thermal conductivity above and below the freezing point. Anisodiametric particle systems are studied for their effective thermal conductivity, particularly the case where the particle conductivity greatly exceeds that of the binding medium [50A]. Solutions with metallic powders of differing nature and dispersivity are also considered and the results compared with selected experimental data.

CHANNEL FLOW

Several studies of channel flow dominated by separation regions were given: heat transfer coefficients were found and a flow and surface temperature visualization study was made in the recirculation zone downstream of an orifice in a circular tube [37B]. It was found that the location of maximum heat transfer was not the reattachment point. Heat transfer and fluid flow analyses were made for laminar flow in cavities upstream of a forward-facing step and downstream of a backward-facing step [41B]. Experimental results were presented for heat transfer in rectangular ducts with sharp-edged inlets [36B] and in corrugated ducts

[27B] where flow visualization showed large recirculation zones adjacent to the rearward-facing corrugation facets. Spirally-corrugated tubes of varying helix angle were experimentally studied where it was shown that the corrugated tubes gave a larger heat transfer to pumping power ratio than given by smooth tubes [11B]. Experiments were made for heat transfer in ducts containing uniformly-spaced arrays of circular pin fins [22B]. A criterion for evaluating heat transfer promoters which uses the heat transfer coefficients and the energy dissipation was proposed [32B]. Based on this criterion, promoters that increase turbulence in the boundary layers are more effective.

The following studies are for channel flows dominated by fluid property effects: the effects of thermal entry length, polymer degradation, and solvent chemistry were shown to be important in the evaluation of drag and heat transfer in turbulent pipe flow of viscoelastic fluids [17B]. The thermal entry region in a rectangular duct was theoretically and experimentally investigated for flow of a highly viscous Newtonian fluid [25B]. The governing equations for laminar fully-developed flow and heat transfer in a curved tube were numerically solved [14B] for non-Newtonian fluid behavior and approximate analytical solutions of channel flow of non-Newtonian fluids with viscous heating were presented [5B]. An experimental investigation was made showing pressure drop and mass transfer in aqueous solutions of polyox in turbulent pipe flow [35B]. It was found that centrifugal pumps cause rapid shear degradation which reduces the drag-reducing properties of the fluid. A multi-layered velocity profile applied to drag-reducing fluids flowing in a pipe was used to predict the effects of diameter on friction and heat transfer [20B]. Numerical predictions were made for heat transfer with constant wall heat flux to low Prandtl number fluids in the turbulent entrance region and in developed pipe flow [6B]. The influence of axial conduction in low Prandtl number turbulent flows was investigated [19B]. An analysis was made of the unsteady flow phenomenon between infinite cylinders where the inner cylinder rotates [2B]. The unsteadiness, called thermal runaway, is seen in injection molding where the fluid thermal conductivity is low and the viscosity decreases rapidly with temperature. The influence of tube dimensions and flow rates on supercooling-freezing flows was experimentally evaluated [24B], and data necessary for the design of waste-water treatment facilities was given. An experimental method was presented for measuring the flow pattern and heat transfer in liquid–liquid two-phase annular flows [28B]. A model was proposed for momentum and heat transfer in a two-phase upward bubble flow in an annulus [33B]. When void fraction profiles are given, the model can predict skin friction, wall heat transfer coefficients and profiles of temperature and velocity. Heat transfer and axial dispersion in batch bubble columns was investigated [4B]. Solidification of steady turbulent pipe flow was analyzed and a method was developed for predicting the onset of freeze-shut [8B]. Expressions for temperature and concentration profiles were analytically found for turbulent flow of a gas in which there is a single reversible reaction that does not go to equilibrium [23B]. Numerical solutions are presented for turbulent pipe flow of dissociating nitrogen tetroxide in equilibrium [1B]. Intraparticle forced convection was considered to explain experimentally-observed changes in effective diffusivity with flow rate in fixed-bed reactors [31B]. Such interactions can result in design errors of considerable magnitude. Combined radiative and convective heat transfer from laminar and turbulent flows was experimentally and analytically studied and a similitude parameter was presented [38B]. A system of equations for the unstable flow on an inclined plane channel with ion mass transfer was developed and solved [18B]. A system of three-dimensional vortices superposed on the flow was studied in the analysis.

Several channel flow studies which focused on turbulence effects were presented. In one, a method of calculating the characteristics of axisymmetric swirling and non-swirling turbulent recirculating flows in wide-angle diffusers was described and appraised [12B]. The differences between experiments and calculations were found to increase with swirl number. Fluid mechanics and mass transfer measurements were made for turbulent flow in triangular ducts [40B]. In the laminar or transitional flow near the apex, a remarkable change in turbulent intensity and space correlation was detected and the turbulent characteristics near the walls were observed to be different than those found in round tube flow. Temperature and velocity fields close to the free surface in an open channel flow were measured where it was found that in the fluid near the free surface vertical motions are damped while spanwise and streamwise motions are promoted [15B]. Experiments in an accelerating turbulent flow between converging parallel plates showed lower exit Nusselt number than at the inlet suggesting relaminarization due to acceleration [39B]. Prediction of these trends was successful with the K-KL model of turbulence.

Several of the channel flow studies dealt with buoyancy effects. One is a numerical study of turbulent vertical pipe flow of supercritical carbon dioxide [29B]. Numerical results were presented also for developing combined forced-free laminar boundary-layer flow in a vertical concentric annulus with a rotating inner cylinder [7B]. A semi-analytical correlation was developed for laminar mixed convection [13B] and a study of intermittent/slug flow heat transfer was made [34B] in horizontal tube geometry.

Pulsating flow effects on heat transfer were seen in several papers. The influence of superimposed pulsation on heat transfer in a heat exchanger geometry was studied where pulsation was found to improve the overall Nusselt number appreciably [9B]. An analysis was presented for fully-developed laminar pulsating flow in curved tubes [30B]. There was considerable variation in peripherally-averaged Nusselt number with varying amplitude ratio, frequency, Reynolds number, curvature, and Dean and Prandtl numbers. The effect of induced fluctuations of the turbulent flow in a slotted channel was experimentally investigated [10B].

Other channel flow studies include one of mass transport in a two-dimensional channel due to shear-Couette flow including cases with a moving wall or chemical reaction [3B]. Laminar flow and heat transfer analyses were made in annular-type crevices of various inclinations and eccentricities [42B]. It was found that inclination can affect the flow and heat transfer rate significantly, especially when eccentricity is large. Experimental results were presented for laminar flow heat transfer downstream of a 180° bend [21B]. The effects of the bend were less important than natural convection effects in the flow downstream of the bend. A correlation of experimental data for annular channel turbulent flow of gases was presented [26B] and a presentation was made of several important problems where similarity methods had been successfully applied [16B].

BOUNDARY LAYER AND EXTERNAL FLOWS

The majority of papers in the area of boundary layers are concerned with laminar and turbulent boundary layers on flat and curved surfaces. In laminar boundary layers, the 'unsteady' situation is receiving increasing attention. Studies have also been reported on flows over cylinders and spheres.

The unsteady heat transfer from a flat plate to an oscillating airflow has been studied experimentally [20C]. Nonsimilarity numerical solutions have been obtained for heat transfer in unsteady laminar boundary layers [29C]. For a non-Newtonian fluid, the unsteady heat transfer in a boundary-layer flow over a wedge has been considered [23C]. Boundary layers on moving surfaces are often important; both laminar and turbulent boundary layers on nonisothermal moving surfaces have been studied [33C]. An investigation has been made for heat and mass transfer in falling liquid films [42C]. Conjugate heat transfer in a laminar boundary layer has also been considered [11C]. Reference [49C] deals with the influence of temperature-dependent properties on the heat transfer in a flat-plate laminar boundary layer. Heat transfer can influence transition to turbulence; this effect for a compressible boundary layer on a flat plate has been considered [48C]. A method of solution has been presented for an unsteady thermal boundary layer controlled by diffusion [37C]. Dispersion by laminar flow has been discussed [39C]. The interaction of a small drop with a solid plane has also been considered [30C]. Reference [7C] is concerned with heat transfer in a laminar flow with a phase-change boundary.

Literature dealing with turbulent boundary layers provides new experimental data or contributions to mathematical modeling of turbulence. The relaminarization of a turbulent boundary layer under the action of a strong favorable pressure gradient has been studied experimentally to uncover the structure of the flow [31C]. On the other hand, the turbulent boundary layer under a strong adverse pressure gradient has also been considered [3C]. Reference [12C] discusses the influence of transition on heat transfer to the turbine blades. A turbulence model based on the concept of turbulent point heat transfer has been considered [22C]. Reference [27C] deals with the stagnation point region in the presence of blowing from the surface. Heat transfer from impinging jets has been studied in ref. [6C] while ref. [9C] is concerned with the stagnation point of a jet flowing over a baffle.

Some papers have considered the flow and heat transfer over cylinders and spheres. Reference [43C] describes a study of the unsteady heat transfer to a cylinder in cross flow. Heat transfer from fine wires and cylinders in a corona wind has been considered [26C]. A study is reported for heat transfer around a cylinder at high blockage ratios [24C]. The problem of variable properties is addressed in ref. [15C] with reference to the boundary layer on a moving continuous cylinder. Reference [25C] describes an investigation of flow and heat transfer around two circular cylinders. Since tube banks or arrays of cylinders are used in many applications, some studies have focused on their behavior. Heat transfer to tube banks is considered for in-line tubes in ref. [2C] and for staggered tubes in ref. [1C]. Low-velocity flow past arrays of cylinders has been studied [41C]. Heat transfer to horizontal tubes in a fluidized bed has been investigated [21C]. Reference [32C] deals with single rods with three-dimensional roughness. Heat transfer from single spheres in low Reynolds number flow has been considered [13C]. Experimental measurements have been reported for heat transfer through a sheared suspension of rigid spheres [16C].

FLOW WITH SEPARATED REGIONS AND THROUGH POROUS MEDIA

Separated regions and jets

Fluid flow and heat transfer in the separated region of a circular cylinder at subcritical Reynolds numbers can be influenced by locating two small cylinders in the separated shear layers [13D]. The effect of a missing cylinder in the twelfth row of a bank of cylinders in cross flow was studied by measurements and visualization with oil lampblack at Reynolds numbers Re_d between 1270 and 8900 [34D]. It was found that the free space causes a change in the heat transfer coefficient on the neighboring cylinders up to 10% for staggered and up to 3% for an in-line element. Maldistribution of the flow created by partial blockage of the inlet cross section of a tube bank [35D] increased the heat transfer by 30–40% in the first few rows of tubes with an additional pressure drop of several velocity heads. An array of 6 × 6 pin fins on a flat surface exposed to an oncoming longitudinal flow which turns to a cross flow was studied experimentally in a Reynolds number range between

500 and 5000 with the result that the Nusselt number was found to be independent of the ratio of height or spacing to fin diameter when correlated with the longitudinal velocity [33D].

Heat transfer coefficients on the upstream side of a perforated plate positioned normal to an incoming flow can be described by the equation

$$Nu = 0.881\,Re^{0.476}\,Pr^{1/3},$$

in which the Nusselt number is based on the ratio of the modular area to the hole spacing as a characteristic length and the Reynolds number on the hole diameter [32D]. A numerical computation of wall jets flowing over the surface of a cone with axial upstream direction demonstrates that a two-equation model of turbulence is successful in predicting experimental results for various cone angles [29D]. A numerical study of wall heat transfer in the recirculating flow region of a confined jet demonstrates that the maximum heat transfer coefficient can occur ahead of the reattachment point [14D]. Liquid crystals were used to obtain the field of isotherms on a flat plate exposed to a normally impinging single jet or an array of impinging jets [11D]. Reference [20D] is a review of experimental and analytical data on heat and mass transport in turbulent liquid jets and shows that the turbulent transport has only a minor effect on mass transfer for the parameter range investigated. This includes new experiments for evaporation of turbulent jets.

Porous media

A linear stability analysis studies the influence of permeability upon the onset of convection in a porous medium [27D]. Exact solutions in ref. [23D] describe free convection in two-dimensional porous cavities of various cross sections at small Rayleigh number caused by a uniform temperature gradient normal to the gravitational field. Permeability of a porous medium contracts the cells and dampens the convection process according to a nonlinear analysis [24D]. A finite-difference technique was used to study convection in horizontally confined layers as they occur in fracture zones in the ground [18D]. Convection in a fluid-saturated porous layer is also analyzed [26D] as it is caused by sudden heating or cooling in the upper and lower boundaries or by distributed heat sources. The boundary shape is determined for a cooled porous region by conformal mapping, requiring that it result in a uniform surface temperature when the surface is subjected to nonuniform heating [31D]. Pulsatile flow in a heated horizontal or vertical porous channel is also analyzed [3D]. Inclusion of the thermal dissipation term in the energy equation describing flow in a porous medium demonstrates that its effect is negligible for natural convection [9D]. Finite-amplitude analysis is applied to thermohaline convection for a porous layer saturated with a two-component fluid [25D].

A number of papers dealt with natural convection in a porous material for conditions where the effect of capillary forces becomes important. A randomized three-dimensional network was used as a model of a porous medium to study two-phase flow through it [17D]. Permeability, relative permeability, and capillary pressure were calculated and compared with experimental results obtained on a granular bed of sand and glass spheres, and a sintered glass bed. A method was presented to calculate the hydraulic conductivity of porous media (soils) using a model considering several bundles of capillary tubes with statistically distributed diameters arranged in series [22D]. The results agreed best with experimental data when five bundles were used. The departure of the phase change of water in a porous medium from local thermodynamic equilibrium was investigated [2D]. The contribution of surface phenomena for porous bodies with unsteady heat and mass transfer was applied to the analysis of the wet bulb thermometer [8D]. A numerical analysis of heat and mass transfer within an intensely heated unsaturated porous medium indicates the existence of a dry and a wet zone and determines the temperature, pore pressure, and moisture distribution as a function of time as well as the vapor release from the surface [5D, 6D]. A continuum model and Darcy's equation with properly assumed vapor and liquid permeabilities are used. The stability of a moving condensation front in a porous layer was analyzed as a contribution to the understanding of the process of oil recovery by steam injection [37D]. It was found that lateral heat losses can have a significant influence. Sodium boiling was found to create non-rewetting hot spots and dryout as well as fluidization in a granular bed simulating debris in liquid metal reactors [7D]. An exact constant property solution of the desublimation processes in a constrained porous medium is based on heat conduction in the frozen and conduction and diffusion in the gaseous regime [16D].

A number of papers published in the Soviet Union dealt with heat and mass transfer in capillary-porous media including the phase composition of moisture [21D], vaporization in a porous membrane [15D], and thermal moisture conductivity of colloidal porous bodies [30D]. Generalized calculations of the kinetics of drying are also presented [28D].

Fluidized beds

Heat transfer between a wall and a two-dimensional fluidized bed was studied experimentally and the results were compared with several heat transfer models [12D]. Bubbling was recorded by a high-speed camera. The Adams–Welty model for heat transfer to a horizontal cylinder in a large particle fluidized bed was confirmed experimentally [4D]. It was found that the range of applicability of the model is wider than originally assumed. Coupled convection and conduction affecting heat transfer in a fluidized bed was studied based on a single particle model [1D]. The Adams–Welty model was used to describe convective heat transfer and was combined with transient conduction. Methods are presented which predict heat and mass transfer coefficients in a fluidized bed including a new model describing heat transfer from the solids in the bed to a wall using the kinetic theory of gases concept [19D]. A mechanistic theory for heat transfer between fluidized beds of large particles and immersed surfaces uses a model in which the solids are distributed around the heat transfer surface in unit orthorhombic cells [10D]. Heat transfer is composed of convection and unsteady-state conduction.

Heat transfer coefficients to a flowing granular material are found to increase with increasing velocity up to a maximum and then to decrease again [36D].

NATURAL CONVECTION—INTERNAL FLOWS

Studies on buoyancy-driven convection in enclosures continue unabated. There is apparently an increase in the number of papers related to heat transfer in horizontal layers heated from below in which a number of special effects can be considered, including nonlinear post-stability phenomena. The natural convection in layers in which there is a horizontal temperature gradient is an interesting proving ground for numerical studies, and both experiments and analysis on this geometry have been reported. Other important phenomena include the effect of internal energy sources, convection in porous regions, double-diffusive convection where temperature difference and concentration difference contribute to the buoyancy variations, and mixed convection where forced flows and buoyancy both influence the flow and heat transfer.

Reports of natural convection in horizontal layers of fluid heated from below include the effects of boundary conditions varying with time and position, the influence of maximum density points in fluids such as water, and the importance of sidewalls. A number of optical investigations of such convection have been described. Energy theory is used to predict stability in a suddenly-heated or cooled fluid layer [52F]. Following a step change in boundary temperature, the stability of a horizontal layer in a high Prandtl number fluid can be calculated using the depth of penetration of the thermal layer [34F]. An analysis shows variations in the critical Rayleigh number when the temperature difference varies across one of the horizontal surfaces [75F]. Slightly non-horizontal upper and lower surfaces lead to a material modulation of post-stability rolls [16F]. Large-scale circulation can occur with convection in a shallow sloping container [17F].

Thermal convection in a horizontal layer of water in which 4°C (the maximum density point) occurs within the layer can produce quite interesting phenomena. One study shows different regions of convection in such a layer heated from below [48F]. In another study in which all walls of a rectangular cavity are decreasing linearly with time, the influence of the maximum density point on flow patterns has been calculated [56F].

A perturbation analysis of Bénard flow with two free surfaces finds the influence of the Rayleigh number on the number of cells present [26F]. In low Rayleigh number convection, the Prandtl number is found to set the size of the convection cell [45F]. The influence of variable viscosity on critical Rayleigh number has been analyzed over a large range of viscosity ratios [64F]. A numerical analysis of three-dimensional time-dependent equations shows the transition from periodic motion to a quasi-turbulent flow [47F]. Convection in a square box heated from below has been analyzed over a range of Rayleigh numbers considering different Prandtl number fluids [46F]. Finite-amplitude rolls are found in a long channel heated from below [24F].

Analysis of thermal convection in vertical cylinders heated from below includes a study of the transient phenomena in which a moving front of heated fluid moves up from the lower surface [43F]. In a low aspect ratio vertical cylinder, the convective motion is found to be non-axisymmetric [57F]. A detailed description is provided of precision measurements of thermal convection in a vertical cylinder in which a fluid is maintained at very low temperature [7F].

Experiments on Bénard convection include use of a laser-Doppler velocimeter to study the flow structure at low Rayleigh numbers [27F]. A holographic interferometer indicated the stream lines and rolls in such flow [71F]. Transitions in the flow pattern at various Rayleigh numbers were examined by optically studying the scale size of the flow pattern [60F]. An interferometer was used to study convection in a layer of visco-elastic fluid [25F].

Unsteady flow has been examined in a stratified water layer cooled from above [73F]. Natural convection in a heated open cavity becomes unsteady at low Rayleigh number when the cavity faces upward [53F]. An analysis considers the flow and heat loss from a free surface in an open channel extending from a large body of liquid [32F].

Numerous studies look at flow in a rectangular region which is heated on one side and cooled on the other. Some of the channels are completely enclosed while, occasionally, attention is directed toward an open channel. A non-boundary layer solution has been obtained for the flow in a vertical open channel [51F]. Optimum spacing to minimize heat flow through a double pane window is generally found to be that which gives transition to the multi-cellular flow regime [36F]. Low Rayleigh number flow in a differentially-heated open vertical well has been analyzed [18F].

Measurements on convection between vertical plates agree with earlier numerical predictions [78F]. A holographic interferometer has been used to study convection in a very narrow vertical layer heated from below [37F]. Convection across a vertical array of enclosures has been analyzed to examine the potential for designing a system that primarily permits heat flow in one direction [13F]. A vertical gas layer to be used as an insulating wall can be optimized by dividing it into a number of parallelogram-shaped enclosures [3F]. In a related work, the effect of radiation on experimental results in cavity flows has been analyzed [4F]. A numerical solution of convection in two adjacent vertical channels whose common wall acts as a thermal communication link has been presented [63F]. Partitions are found to have a significant influence on heat transfer across a differentially-heated enclosure [5F]. Linear theory has been applied to study the stability in a fluid found adjacent to a melting ice layer [28F].

The onset of convection in a vertical layer which is suddenly heated from the side has been analyzed [33F]. Experiments indicate a very slow approach to the steady state for transient differential heating of a shallow fluid layer [79F].

An approximate analysis for laminar flow in a differentially heated shallow layer compares favorably to numerical solutions [69F]. A numerical solution of flow in a tall narrow cavity shows a significant effect of aspect ratio on the rate of heat transfer across the cavity [31F]. The effect of variable temperature of the top and bottom walls on a differentially-heated rectangular enclosure has been examined [59F]. The Nusselt number along an open vertical square duct has been calculated for boundary conditions of constant temperature and constant heat flux [55F].

Heat transfer across differentially-heated inclined layers is important in a number of applications. Experiments with air in inclined and vertical layers lead to a correlation valid for Rayleigh numbers up to 10^7 and for a large range of aspect ratios [20F]. Radiation interaction can play a key role in measurements in layers of air [19F]. Numerical studies show the influence of conducting walls between neighboring inclined rectangular cells [50F]. Experiments using water in low aspect ratio cavities indicate different flow regimes at different angles of inclination [77F]. Finite-element analysis has been used to predict the natural convection in inclined rectangular cavities [65F].

Experiments on a horizontal layer with internal energy sources include the effect of external heating [35F]. Bifurcations are found in a solution to internally-heated flow in a vertical channel [70F].

Flow set up in a rectangular cavity all of whose walls decrease with time has been analyzed [72F]. A study of stability in the flow of a fluid layer heated from below which is also rotating about a vertical axis includes a comparison between experimental and theoretical results [9F].

A steady-state solution is found for convection in a triangular cavity heated on one side and cooled on another [2F]. A combined numerical and experimental study shows that axial spacers can reduce the natural convection heat transfer across an annulus by as much as 70% [39F]. Bi-polar coordinates are used to analyze natural convection in the annulus between eccentric horizontal cylinders [12F]. Numerical calculations for natural convection in an annulus have been extended into the turbulent flow regime [23F]. Convection inside a heated horizontal cylinder has been studied to predict melting in a phase-change thermal energy storage device [58F]. Convection patterns in a spherical shell, as might occur in the earth's mantle, are explored for low Rayleigh number flow [10F]. Convection in a region bounded by two vertical concentric isothermal cylinders with the inner one shorter than the outer has been examined [11F].

A review of experiments and analysis led to a correlation for predicting the heat transfer from a buoyant plume to an unconfined ceiling [14F]. Plumes above a ring heater have been studied to simulate flow in the atmosphere, particularly as this relates to a specific fire [38F]. Computations of the natural convection from a two-dimensional source have been used to predict smoke flow from a fire [44F].

Studies of natural convection in porous media have application in geo-physical phenomena as well as to optimize insulation systems. Energy methods have been used to study the stability of natural convection flow in a porous substance [54F]. Measurement and analysis indicate the critical Rayleigh number and the Nusselt number at low Rayleigh numbers for a porous medium heated from below [6F]. Buoyancy effects in flow through porous media have been studied [41F]. An analysis shows the effect of natural convection on insulation in an attic-shaped enclosure [8F]. The onset of flow has been calculated for a saturated porous medium with fluid above it and with internal energy sources [61F].

Double-diffusive convection occurs when the buoyancy term has components due to two diffusive phenomena. These usually are thermal and mass diffusion and show up as variations in temperature and concentration. Mass diffusion effects are considered in analyzing the stability of a binary mixture heated from below [15F]. Double-diffusive convection has been studied at a sufficiently high Rayleigh number to simulate conditions in a solar pond [76F]. The development of flow in a salt-stratified solution heated from below with isothermal boundaries has been examined with a Mach–Zehnder interferometer [42F]. The Galerkin method is used to predict the flow in a differentially-heated inclined fluid layer with a stable concentration gradient [68F]. The critical parameters leading to the onset of cellular flow are found with a heated vertical wall adjacent to a stably-stratified fluid [67F]. In a related paper, convection cells are observed adjacent to the heated wall [66F].

Natural convection loops or thermo-syphons are useful in many systems including solar heaters; they also simulate natural convection cooling of nuclear reactors. A two-dimensional analysis of the flow and heat transfer in a toroidal natural convection loop agrees with earlier experiments [49F]. A one-dimensional analysis shows the transient thermal-hydraulic behavior in a toroidal thermo-syphon [74F]. An analysis has been conducted on a natural convection flow-driven system as might occur in an ocean thermal power device [1F]. Facilities have been designed to study natural convection in a liquid-metal fast-breeder reactor shut-down heat removal system [29F].

Mixed convection or combined natural and forced convection occurs when body forces affect the forced flow in a heat transfer system. A numerical solution of the laminar mixed convection in the entrance region of a horizontal pipe which is valid for arbitrary Prandtl numbers has been offered [30F]. Experiments with a laminar flow in such a geometry have been conducted over a range of Graetz, Reynolds, and Rayleigh numbers [80F]. Two-dimensional flow about a horizontal heated cylinder between two vertical walls includes the effect of mixed convection [22F]. Experiments on flow in an open vertical channel with one heated wall and a heavy transpiring gas passing through the wall have been conducted [40F]. Calculations describe the combined free and forced convection within a heated vertical cylinder with flow passing through small openings in the top and bottom walls of the cylinder [62F]. Combined convection around a vertical plate with a forced flow parallel to it shows different flow patterns in different regions along the plate [21F].

NATURAL CONVECTION—EXTERNAL FLOWS

An integral equation formulation for natural convection problems is developed and illustrated and theorems are proved which establish the properties of the eigenvalues and eigenfunctions of a linear integral operator that appears in the analysis [34FF]. By applying appropriate coordinate transformations and the Merk series, the governing momentum and energy boundary-layer equations for a vertical plate with nonuniform surface conditions are expressed as a set of coupled ordinary differential equations that depend on a wedge parameter and the Prandtl number [36FF]. The existence of multiple steady-state solutions in natural convection flow was demonstrated for the case of laminar flow adjacent to a vertical, heated or cooled, flat surface submerged in quiescent cold water [10FF]. The computed results for transient laminar natural convection flow adjacent to a vertical surface subject to a uniform heat flux boundary condition show good agreement with the experimental measurements [27FF]. Free convection heat transfer near the leading edge of a semi-infinite vertical plate with uniform heat generation has been analyzed numerically and the results were found to be in good agreement with experimental data [21FF]. In a combined theoretical and experimental study, techniques of fine wire thermocouple thermometry and real fringe laser-Doppler anemometry were used to study the boundary-layer flow adjacent to a vertical isothermal hot plate with high surface-to-ambient temperature difference [6FF]. The natural convection flow due to isolated heated elements located on a vertical adiabatic surface, a problem of particular relevance to electronic circuitary cooling, has been studied analytically [17FF]. The problem of laminar free convection adjacent to a vertical wall with an arbitrarily prescribed transpiration rate has been investigated using the method of strained coordinates [19FF].

The technique of live-fringe holographic interferometry has been used in an investigation of convective heat transfer in air beneath a heated horizontal circular plate [13FF]. Interferometric studies of free convection above a horizontal heated plate revealed periodical flow instabilities which resulted in large variations in local Nusselt numbers [37FF]. The vortex instability characteristics of laminar free convection flow over horizontal and inclined isothermal surfaces are studied analytically by linear theory [8FF]. It is shown that the principle of exchange of stability is not always accomplished in the Rayleigh–Bénard problem for fluids with internal structure [25FF]. A mathematical model has been developed for determining the dynamic response of a salt-stratified solution to heating from below, and predictions have been compared with experimental results [5FF]. Interfacial stability in liquid drops' evaporation of flat plates at room temperature was studied by both direct photography and laser shadowgraphy [38FF].

Numerical solutions for steady two-dimensional free convection from a horizontal circular cylinder are obtained for small Grashof numbers by the method of series truncation [30FF]. The evolution of the boundary layer formed by the sudden heating of a horizontal circular cylinder in air was analyzed assuming that the Grashof number is large [32FF]. A two-equation model has been adopted in obtaining numerical solutions of turbulent natural convection from an isothermal horizontal cylinder [12FF]. The method of extended perturbation series is applied to solve for laminar natural convection from an isothermal, thin vertical cylinder [3FF]. Experiments were carried out to determine the average and the local heat transfer by natural convection from the outside surface of isothermal cylinders of different diameters and lengths at different inclinations in both the laminar and the turbulent regions [1FF]. Unsteady low Grashof number natural convection about a sphere is studied when the surface temperature of the sphere is suddenly increased and it is shown that the solutions for the velocity and temperature are expressed in terms of three expansions reflecting the existence of three distinct regions in the plane of non-dimensional radius and time [28FF]. A numerical study of time-dependent free convection heat transfer from a solid sphere to an incompressible Newtonian fluid has been carried out for Grashof numbers between 0.05 and 12 500 and for Prandtl numbers of 0.72, 10 and 100 [14FF].

A study was made of the natural convection of cold water between two horizontal concentric cylinders with constant surface temperatures [24FF]. Nusselt numbers were measured for an in-line array of short horizontal cylinders that were affixed to a convectively participating vertical plate and, for the most part, the Nusselt numbers for the wall-attached cylinders fell below those for the classical horizontal cylinder of infinite length [33FF].

A theory is reported that explains the flickering motion of turbulent plumes as well as their large-scale sinuous structure [4FF]. An analytical study of the laminar flow in axisymmetric thermal plumes and buoyant jets in stably stratified media is reported [16FF]. A detailed experimental investigation has been carried out to study the trajectory and other thermal characteristics of a buoyant jet discharged at an inclination to the vertical buoyant force [29FF]. Merging buoyant jets discharged in a cross flow were investigated experimentally using a unique visualization technique [15FF]. An experimental study of a vertical turbulent jet with a negative buoyancy showed that the width of the upflow spread linearly with respect to the distance from the nozzle exit, whereas the width of the whole jet was almost constant [23FF].

A matched asymptotic technique is used to construct inner and outer expansions including, for the first time, both mixed convection and higher-order boundary-layer effects in order to analyze mixed convection flow over a vertical semi-infinite surface with uniform heat flux [7FF]. Numerical calculations of the time-varying temperature and velocity profiles are presented for transient aiding mixed convection flow adjacent to a vertical flat surface [26FF]. The mixed convection flow that arises due to a finite heated element located on a vertical adiabatic surface in an external flow, aligned with the surface, is studied analytically [18FF]. A correlation was developed for the average Nusselt number for the case of laminar mixed convection from a vertical heated surface in a cross flow [11FF]. A heated flat plate was tested in a wind tunnel to study mixed convection in both upward and downward positions [35FF]. The buoyancy force plays an important role in defining the flow field in mixed convective flow over a semi-infinite horizontal plate with vectored mass transfer [9FF]. Measurements of the streamwise and vertical velocity fluctuations and temperature fluctuations in a thermally stratified flow in an open channel under unstable conditions indicate that the contribution to the total turbulent momentum flux from the sweep motion of large amplitude becomes greatest in the free surface region [22FF]. The combined effect of forced and free convection on the unsteady laminar incompressible boundary-layer flow with mass transfer at the stagnation point of a three-dimensional body with time-dependent wall temperature has been studied [20FF].

An analysis of laminar, free convection, diffusion flames burning on a vertical fuel surface is presented [31FF]. Flames that spread vertically down thermally thin fuels at the same Damkoehler number have the same dimensionless temperature fields although their physical size and hence temperature fields might be quite different [2FF].

CONVECTION FROM ROTATING SURFACES

Heat transfer by forced convection has been considered in a rotating concentric annulus [4G]. The situations involving eccentric cylinders or disks have been investigated [6G, 1G]. Reference [2G] presents a numerical solution obtained by the finite-element method for the rotating flow in a skewed shrouded rotor. Convection in a rotating layer has been considered [5G]. Reference [8G] deals with the laminar heat transfer from the surface of a rotating disk. Thermal cellular convection in rotating rectangular boxes has been considered [3G]. Heat transfer coefficients are reported for a cup-like cavity rotating about its own axis [7G].

COMBINED HEAT AND MASS TRANSFER

Systems in which both heat and mass are transferred are manifold. They include processes such as film cooling and transpiration cooling, where mass is fed into the boundary layer on a wall to protect the surface from a hot gas stream flowing over it, jet impingement cooling, and processes in which jets or equivalents are used for direct contact heat transfer. Other systems include applications in chemical reactors and in the drying of paper, film, and agricultural products.

A mixing length model is used to correlate the results for film cooling with near tangential injection through a discrete hole [11H]. With slot injection on a turbine blade, variations in the angle of attack of the blade affect the film cooling performance on both the pressure and suction surfaces [10H]. For film cooling injection through discrete holes, the heat transfer performance is strongly affected by the nature (laminar vs turbulent) of the injected flow [6H]. A high heat transfer coefficient in the immediate vicinity of film cooling injection holes has been demonstrated using a mass transfer system [5H]. High free stream turbulence significantly enhances heat transfer to a porous surface through which fluid is transpiring [12H]. A study of the influence of boundary-layer suction and injection on heat transfer in a supersonic boundary layer includes the effect of separation induced by a transpiring gas [3H].

In some direct contact heat transfer systems, a jet of one fluid enters another fluid in order to transfer heat between the two fluids. The hydrodynamics of a liquid jet as it would affect such heat transfer has been described in a companion pair of studies [8H, 9H]. A correlation has been obtained for heat transfer from an impinging jet to a solid surface on which it impinges with and without a cross flow [4H].

The heat and mass transfer across an air–water interface is strongly affected by the surface roughness produced by even moderate air speeds [7H]. The effect of swirl significantly increases the heat and mass transfer from an ablating surface [15H]. A model for combined heat and mass transfer shows the importance of high gas velocity in controlling the temperature of stored agricultural products [2H].

A correlation has been obtained for heat and mass transfer in tanks of liquid with mixing due to stirring and gas injection [1H]. The importance of simultaneous heat and mass transfer in gas absorption has been analyzed [14H]. A thermodynamic approach has been used to describe combined heat and mass transfer in a gas–solid system [13H].

BOILING

Nucleate boiling

The advantageous high heat transfer coefficients provided by nucleate boiling continue to promote interest in this phenomenon. Suggested equations governing the nucleate boiling curve have been compiled from a variety of sources, including only those relations dependent upon fluid properties alone so as to avoid bias due to the properties of the surface [40J]. Correlations for bubble departure diameters, bubble generation frequencies, and resultant heat transfer coefficients in nucleate boiling have been developed using the law of corresponding states and have been shown to fit well available data for several different fluids [10J]. Contact angle hysteresis within natural cavities, associated with micro-roughness and surface heterogeneity of cavity walls, has been argued to be the predominant barrier to boiling incipience [18J]. Measured deactivation superheat for an artificially prepared nucleation site in methanol was shown to agree well with the surface superheating required for the balance of pressure and surface tension forces [30J]. Previous investigations of this nature had been limited to water with its poorer wetting characteristics. Boiling characteristics of a natural surface were related to the real surface profile with attention paid to micro-roughness [38J]. In another study at the microscopic level, large changes of the local heat flux at a single isolated nucleation site were observed coincident with significant variations in the product of bubble departure diameter and bubble frequency, all with little change in the local wall superheat [69J]. A technique has been described to evaluate the stability of nucleate boiling on nonisothermal surfaces [39J]. Long-term temperature behavior of steel tube walls was reported, indicating the consequence of corrosion product accumulations [33J]. Certain sponge-like deposits were determined to be particularly undesirable.

Considerable interest has been shown in the development of commercially producible surfaces to enhance nucleate boiling. Carefully prepared, highly regular surfaces are still being studied for more control over the parameters which might be optimized. In one of these latter studies a fiber optic system provided bubble departure diameter and frequency information at low heat fluxes [56J]. Substantial improvement of nucleate boiling heat transfer coefficients were measured using porous metallic matrix surfaces [7J, 20J, 49J], although boiling curve hysteresis was cited as a potential problem in cases of very critical temperature control [7J].

The relative contributions of evaporative heat transfer and single phase convection promoted by bubble agitation remain a topic of interest. A simultaneous boiling and ion diffusion experiment was reported to demonstrate the dominance of the convective mechanism [11J]. Another experiment modeled the bubble-induced liquid circulation near the boiling surface by bubbling gas through a porous plate into a liquid. Tabulated data and some comments on the method are presented [47J]. Nucleate boiling of binary liquid nitrogen/argon mixtures were studied [68J]. Both evaporative and sensible heat transfer mechanisms were concluded to be impeded at maximum vapor–liquid mole fraction differences.

Most studies in the past have dealt with nucleate boiling at atmospheric or higher pressures. Subcooled nucleate boiling at subatmospheric pressures was observed to follow a substantially different relationship between wall superheat and liquid subcooling than at higher pressures [12J], while four distinctly different patterns of boiling were observed, dependent upon pressure and heat flux, for subatmospheric saturated boiling [25J].

Fundamental questions of bubble growth dynamics are still being addressed [17J]. A perturbation method was applied to the pre-asymptotic behavior of thermally controlled bubble growth [13J]. The method of characteristics was applied to gas bubble implosion [65J]. Results of the numerical analysis show the formation of jets and detachment of small bubbles. The effect of the liquid viscosity upon the displacement of liquid from the wall during bubbling was studied by means of a hydrodynamic model: an inert gas being bubbled through a porous plate into water/glycerol mixtures of varying viscosities [48J]. Liquid viscosity was concluded to be irrelevant to the departure from nucleate boiling.

Forced convection boiling

Forced convection boiling in tubes or channels is of great concern in the design of steam generating equipment and chemical process development as well as nuclear reactor design. Forced convection boiling data for flow in tubes has been correlated using a superposition of either of two single phase forced convection correlations (one for subcooled or low quality flows and the other for high quality annular flows) upon a pool boiling correlation. Agreement with available data for boiling of water is shown to be superior to the agreement of the widely used Chen correlation [9J]. Another forced convection correlation for boiling in tubes has been proposed which is independent of tube diameter and liquid viscosity except for their influence upon the transition from single phase convection to developed boiling [67J]. Existing literature on subcooled flow boiling heat transfer and hydrodynamics in pipes has been summarized [71J].

Widely diversified data for two phase pressure drop and heat transfer coefficients has been correlated for annular flows in vertical upward, horizontal, and vertical downward orientations [24J]. A technique for estimating the distribution of liquid flow between droplets and film in annular flow was presented and compared with data from high-speed motion picture photography [42J]. The extent of the non-evaporating region in downward flowing vertical liquid film evaporator tubes was determined experimentally for various flow rates and pressures [64J]. Heat transfer rates in the non-evaporating regions are estimated to be 4.1–4.5 times smaller than in the evaporating regions. A downward flowing vertical liquid annular film inside a tube with a counterflowing vapor core all in laminar flow was analyzed numerically and compared with experimental results [16J].

Good agreement has been demonstrated between a numerically resolved critical heat flux (CHF) estimation based on an annular flow model and the annular flow segment of a previously presented CHF correlation [35J]. Those same generalized correlation equations for CHF have been shown to be capable of predicting the 'critical steam quality' or 'boundary steam quality' phenomenon reported by many observers in which the critical heat flux falls precipitously beyond some given quality [36J]. The high pressure (HP) regime of that same generalized correlation was examined experimentally using Refrigerant 12 in tubes of 3 and 5 mm diameter [37J]. Data from the smaller diameter tube and from low mass flux experiments with the larger tube were consistent with the above-mentioned correlation and with another correlation in the literature, but at large mass fluxes in the larger tube an anomalous CHF event was detected with a smaller wall temperature excursion and at a location upstream of the end of the heated section of the apparatus. Vertical upward and downward evaporating flows of Refrigerant 113 in a small tube were examined for pressure drop, heat transfer, and CHF data [43J]. Heat transfer coefficients were consistent with those predicted by the Shah correlation originally developed around larger diameter tubes. Existing correlations for CHF, however, underpredicted the measured values. Critical heat flux variations were observed in helical coiled tubes with an imposed heat flux tilt toward the outside surface [31J]. Local or subcooled CHF could be improved or degraded by the flux tilt, or maldistribution, whereas CHF for flows with higher quality was generally reduced by the flux tilt.

A numerical model for post-dryout heat transfer considering three mechanisms: wall/vapor, vapor/droplets, and wall/droplets, was improved by the incorporation of a procedure for determining droplet size distribution [52J]. Wall temperature predictions agreed well with data, and wall-to-droplet heat transfer was estimated to be as much as 10% of the total near the location of dryout. The post-dryout region in horizontal tubes was observed to differ from that of vertical tubes [61J]: dryout appeared to be spread out axially along the tube as the upper surface of the tube dried out before the lower surface, the local wall temperature rise due to dryout was weakened, but wall temperature increased linearly with position downstream of the dryout as contrasted with the nearly uniform downstream wall temperature of the vertical tube. The rewet of dispersed flow film boiling was examined for vertical flow [26J]. Wall thermal properties were found to be insignificant below a threshold mass flux; above that mass flux the minimum temperature increased with mass flux for an Inconel section, but a copper test section was unaffected. A generalized 'heat transfer surface' technique was applied to the analysis of quenching in two phase forced convection water systems [57J]. Caution is recommended in the interpretation of data from quenching experiments. Transient wall temperatures in the post-dryout region were recorded experimentally in response to deliberately imposed system transients [22J]. The temperature–time histories were analyzed qualitatively using the boiling curve, and the dynamics were successfully modeled with a computer simulation. A stability analysis of film boiling has been reported using a steady-state small perturbation method. Below a critical vapor Reynolds number the film has a great tendency to collapse [62J]. Despite the use of a simple model for film thickness, the results reflected experimentally observed trends, and a better film thickness model is expected to improve the prediction of minimum wall temperature and the effects of subcooling.

The state of the art in design methods for multicomponent boiling and condensation in forced convection was summarized with the inclusion of some comparisons with data and some general recommendations for design procedures [60J]. An experimental evaluation of pressure drop in swirled flow boiling of Refrigerant 12 is reported [2J]. Satisfactory correlation was achieved by using an empirical function of the twist ratio of the twisted tape swirl inducer to modify the pressure drop predicted by the Martinelli–Nelson method.

Natural convection boiling

A standard experimental apparatus was proposed for pool boiling experiments so as to produce general, reproducible, and accurate heat transfer data [21J]. Transition boiling of water was the topic of three elements of a four article series on subcooled pool boiling: contamination on a platinum heat transfer surface was shown to improve the transition boiling heat transfer coefficients [27J], large subcooling (around 30 K) resulted in the formation of large voids which collapsed very rapidly, fragmenting into small voids and permitting large heat fluxes [28J], and a proposed model for subcooled transition boiling was supported by simultaneous measurement of heat flux and wall temperature with motion picture photography of bubble events [29J]. Evidence is presented for the existence of two distinct boiling curves in the transition region, transitional nucleate boiling and transitional film boiling [70J]. This hypothesis could explain the discrepancy between observed and hydrodynamically predicted minimum heat fluxes in film boiling since the selection of which transitional boiling curve will be obtained depends on physical parameters which have not been independently controlled in past experiments.

High-speed motion picture photography was used to observe the local behavior of bubbles on the surface of horizontal tubes in an evaporator tube bundle [19J]. A model, only accurate to within an order of magnitude, explained the higher heat fluxes observed at tubes in the upper center of the bundle. Higher heat fluxes were also observed in a study of a finned tube bundle in an evaporator [54J]. The greatest augmentation of heat transfer from these upper tubes was observed at heat fluxes corresponding to the transition from single phase natural convection to nucleate boiling.

In an effort to model boiling on finned surfaces, an experimental investigation of boiling in a narrow confined slot with nonisothermal walls was employed [58J]. Possibilities of improvement over boiling on plane surfaces were reported. Experiments with boiling in smaller gaps were reported using narrow annular spaces, some open at both top and bottom and others open only at the top [4J]. The nucleate boiling heat transfer coefficient was found to improve with decreasing gap width when the annulus was open at the top and bottom, and to be independent of annulus length. With a closed bottom, neither width nor length affected the heat transfer coefficient. For given dimensions, the closed bottom gave greater heat transfer coefficients, but went through a transition to unstable drying and rewetting at lower heat flux than the open annulus case. Critical heat flux was examined experimentally for natural convective boiling of several fluids in vertical rectangular channels heated on one side only [51J]. Little effect was visible for the channel spacing alone, but the aspect ratio, height-to-width, was found to be significant. Heat transfer to vertical and inclined boundaries of volumetrically heated boiling pools was modeled using a two zone scheme which correlated well with data [15J].

Other boiling and evaporation studies

Boiling in a bed of particles confined at the bottom and sides, flooded from above, and heated volumetrically or from the sides has been studied [1J]. A flow visualization experiment demonstrated a dry superheated layer formed at the bottom with a 'capillary' layer of counterflowing liquid and vapor above it. Large unsteady horizontal voids atop this region acted as plenums to feed vapor channels above them in turn. Simple physical models were presented for predicting the heights of the capillary and chimney zones and evaluated parametrically. In another study with a similarly confined bed heated only at the bottom, no dry region was observed, although it was suggested to be possible with sufficiently large heat transfer rates [6J]. Forced flow through a volumetrically heated porous layer was also examined [55J]. Vapor channeling was noted for particles smaller than 1.6 mm, and separate pressure drop models were suggested for particles larger and smaller than that diameter.

Direct contact evaporation was either the goal (evaluation of performance of direct contact evaporators) or an experimental method (determination of the limits of liquid superheat) in several studies. An analytical model for volumetric heat exchange coefficients was presented and compared favorably with data [66J]. A more detailed model examining only the heat exchange at a single droplet/bubble was reported with the principle resistance to heat transfer being a thermal boundary layer in the fluid external to the droplet [59J]. Liquid droplets heated by a surrounding immiscible liquid were filmed as they vaporized to determine qualitative aspects of boiling intensity and bubble growth data [5J]. Violent boiling at atmospheric pressure gave way to slower vaporization at elevated pressures. Results suggested that vapor explosions are unlikely in the case of thermally controlled bubble growth. Very rapid evaporation of butane droplets in heated ethylene glycol were observed at the superheat limit of 105°C [63J]. An interfacial instability was observed, possibly explaining how the rate of vaporization was two orders of magnitude greater than that expected for a stable interface. A correlation for spinodal pressure was developed based on an argument of corresponding states [45J]. This reduces the dependence of calculations upon difficult-to-obtain data on specific volume and surface tension.

Experiments were reported for heat transfer to air/water mist flows from horizontal circular cylinders with various surfaces [41J]. The surface conditions were intended to augment the heat transfer by spreading liquid over as much surface as possible to take best advantage of the evaporative cooling. The effect of incidence angle on mist flow heat transfer from an isothermal flat plate was determined [23J]. At low incidence angles, laser-Doppler anemometry demonstrated that droplet velocity distributions were self-similar and in keeping with the single phase velocity distributions. Heat transfer coefficients increased with incidence angle. Results of an experimental study were presented for mist cooling of very hot tubules [53J]. Three regions were identified; liquid film, dryout, and gas-phase forced convection. The mist flow was found to augment the heat transfer rate by as much as ten times. A technique for estimating the Leidenfrost temperature and the time required for vaporization of a droplet was presented [3J]. The influence of an electric field upon the vaporization of charged droplets was numerically determined [32J]. The augmentation is due to the acceleration of the droplet by the electric field. In another study the influence of the electric field upon the internal circulation of a droplet and the consequent enhancement of heat and mass transfer were addressed [14J]. It was determined that this effect is negligible except when electrical effects are much greater than gravitational effects, and that the apparent enhancement of heat and mass transfer in several preceding experiments must be attributable to effects other than internal circulation of the drops.

Turbulence and surface renewal associated with deep-water convection are important in mitigating the effects of surface active compounds on the evaporation rate of a body of water [34J]. Otherwise, there is an additional diffusive resistance to the evaporation of water through surfactant layers [50J]. Estimations were made of corrections to evaporation rates from a liquid to a flowing gas and vapor mixture [8J]. The transverse mass flux could have a significant effect on the heat and mass transfer, possibly resulting in a departure from the analogy between them.

A small-scale surface probe has been described using a miniature thermocouple in contact with a thin plated surface to detect liquid contact in transition boiling on high temperature surfaces [44J]. Experiments were performed to evaluate film breakdown and bundle depth effects on falling film evaporators proposed for evaporating ammonia in an Ocean Thermal Energy Conversion (OTEC) system [46J]. Film breakdown was observed for low film Reynolds numbers, but variations with depth were not observed.

CONDENSATION

Film condensation

A review of semi-empirical models for film condensation was given [16JJ] and predictions from these models were compared with available experimental data. A model based on absorption and capillary condensation was presented [28JJ] and then used to describe conditions at the contact line.

The case of upward vapor flow inside vertical tubes was analyzed where the results showed complete condensation on the laminar film in a short height of tube [22JJ]. The hydrodynamic and heat transfer processes of condensation or evaporation of a thin laminar wavy-film were analyzed and the results were compared with available data [9JJ, 10JJ]. Measurements were made of the heat transfer coefficients for dropwise condensation on a vertical wall where surface subcooling at the initiation of condensation of 0.03°C was found [13JJ]. Melting of a vertical wall as a result of condensation of a saturated vapor was analytically and experimentally studied [26JJ]. The presence of a melt or condensate layer was found to enhance heat transfer. A closed-form, approximate solution was presented for film condensation on a vertical rectangular fin [4JJ]. The steady flow and unsteady starting flow film condensation processes were investigated with surfaces of differing geometry [21JJ]. Measurements were made of the vapor-phase temperature profiles and rate of condensation for vertical wall condensation of binary vapor mixtures [1JJ]. The data were correlated with a modified Nusselt model. Experimental results were presented for film condensation on vertical surfaces [8JJ] and vertical tubes [3JJ].

A flow regime map was developed for predicting flow patterns [27JJ] and the annular-to-wavy flow pattern transition process was clarified [25JJ]. A theory was presented for condensation of wet vapor and uniformly distributed droplets on a horizontal tube [19JJ]. The heat transfer coefficient was dependent upon the droplet mass flux and velocity as well as the vapor velocity. The vapor condensation rate inside horizontal conduits was analyzed for co-current and counter-current flow of steam and condensate [18JJ]. A higher condensate production rate was found for co-current flow. Experimental results of condensation in finely-finned horizontal tubes were presented where the tube thermal conductivity was shown to have a significant effect [23JJ]. Results were also presented for condensation in a horizontal ten-tube bundle [17JJ] and in sloped single tubes [14JJ, 15JJ].

Condensation from a vapor–gas mixture was analyzed and experimentally investigated to study local characteristics of the process [11JJ]. Analytical and experimental results were presented for condensation in an inverted U-tube condenser where four modes of flow were identified and it was found that non-condensibles significantly aided flow stability [5JJ]. An analysis was made and a correlation was presented for condensation of sodium [20JJ].

Free condensation

Several studies of the problem of steam flowing through a pipe and out the submerged end into a pool of subcooled water were presented. High-speed movies showed that at high rates of steam flow an oscillating jet could be observed, and at low flow rates chugging could be seen [6JJ]. Three intervals associated with periodic flow characteristics of the condensing jet were identified and the dynamic behavior of each event was discussed [24JJ]. A theoretical and experimental investigation was made where it was found that conventional turbulence models established for single-phase flow are appropriate [7JJ]. Dimensionless temperature profiles in the steam jet were found to be independent of steam pressure or ambient liquid temperature [2JJ].

A numerical study was presented for the collapse of a bubble in a three-component, three-phase system [12JJ]. The model predicted collapse appropriately when the bubble is initially small and does not deform during its early life.

RADIATION

There is a substantial number of publications which are concerned with radiative transport in emitting, absorbing and scattering media.

A new approach to radiative heat transfer with scattering is presented and used to obtain the first general solution for radiative equilibrium in a non-gray, plane-parallel medium [46K]. The Galerkin method is applied to solve radiative heat transfer to an isotropically scattering, absorbing, and emitting plane-parallel medium with diffusely reflecting boundaries [41K]. Radiation heat transfer in a planar participating medium which scatters anisotropically is scaled to an isotropic scattering medium. The scaling that gives the best results is the one derived from the $P-1$ approximation [36K]. An approximate approach to radiative heat transfer in an isotropically scattering and non-gray absorbing medium indicates that the predictions for the radiative heat flux and intensity are accurate over large ranges in optical depth and scattering albedo [8K]. Radiative heat transfer in an isotropically scattering and non-gray absorbing planar medium is investigated using wide-band absorption quantities, including the effects of gray absorption and scattering by the scattering components and non-gray absorption by the gaseous components [7K].

The results of radiative heat transfer studies in an absorbing medium using complementary variational principles are in excellent agreement with those using more cumbersome solution procedures [19K]. Comparisons of three approximate numerical methods based on plane-symmetric, gray model (coal particle suspension) for evaluating radiant energy transfer in scattering and heat generating media indicate that the accuracy of flux methods decreases while the accuracy of the differential approximation increases with increasing optical thickness of the suspension [28K]. The coefficients for the weighted sum of the gray gas model are more accurate in terms of total properties over a wider range of temperatures and partial pressure–path length products than previously available coefficients [48K].

Theoretical investigations are reported of unsteady radiative heat transfer through an absorbing and emitting gray medium which occupies a semi-infinite space bounded by a semi-transparent gray plate [32K]. Time-dependent radiative transfer is studied in a semi-infinite medium with a reflecting boundary [18K].

A study of the role of various water clusters in i.r. absorption in the 8–14 μm window region indicates that homo-molecular water clusters larger than the dimer are not responsible for the continuum absorption [49K]. Infrared absorption measurements in the 6.3 μm band of H_2O vapor indicate that the dimerization effect on the monochromatic absorption coefficient and on the integrated absorption coefficient is negligible [34K]. Radiation intensity and emissivity of the 4.3 and 2.7 μm vibrational–rotational bands of CO_2 and of the 5.7 μm band of CO have been numerically calculated and measured over a wide range of parameters of vibrationally non-equilibrium mixtures expanding through the supersonic nozzle of a gas dynamic CO_2 laser [33K]. The K–ε model of turbulence is not completely satisfactory for predicting the temperature distribution and the dynamics of the mixed layer during simultaneous radiant heating and cooling or during cooling of thermally stratified water [54K].

Combined conductive and radiative heat transfer in an absorbing, emitting, and scattering cylindrical medium is studied using the Galerkin finite-element technique which is well suited to this problem because of the ease with which integrals with variable limits can be handled [16K]. The $P-1$ and $P-3$ methods yield results for combined conduction–radiation problems which are in close agreement with exact solutions for one-dimensional planar problems [44K]. Predictions of the effects of wall radiation and conduction on the stability of a fluid in a finite slot heated from below are in reasonable agreement with present and previous experimental data [24K]. Numerical solutions of the contact interface temperature of two semi-infinite media of different temperatures, considering internal thermal radiation and conduction effects, indicate that the technique is relatively simple and accurate [50K]. Results of a polynomial approximation method for the solution of heat transfer by conduction and radiation in an absorbing, emitting, and isotropically scattering medium show that the solution method is relatively simple and converges very quickly to the exact solution [12K].

An analysis of the effects of absorption of radiation by fluids during measurements of their thermal conductivity by the transient hot-wire technique shows that the contribution of radiative transport to the transient heating process means that the thermal conductivity derived from such measurements is systematically in error [38K]. Studies of combined radiation–convection in gray fluids enclosed in vertical cavities show that radiation decreases the intensity of the flow at low Rayleigh numbers and, in contrast, leads to an increased flow in convection regimes [35K].

From radiative flux measurements in the troposphere, heating rates for gases and for aerosols are calculated. Total heating rates of 0.175 and 0.377°C h^{-1} are determined for hazy and foggy atmospheres, respectively [51K]. In connection with scattering and absorption of solar radiation from aerosols in the atmosphere, the optical constants of aqueous solutions of sodium sulfate have been determined for a wavelength range from 2 to 20 μm [2K]. Experimental values of attenuation coefficients and transmissivities of radiant fluxes caused by aerosols consisting of fine metal powders differ significantly from those initially predicted [56K]. Studies of the absorption and scattering of thermal radiation within a dilute cloud of pulverized coal and char indicate that a simple hemispherical absorptivity of 0.89 may be used for heat transfer calculations if the particles can be assumed to act as Mie scatterers, and if the volume fraction of ash and soot particles is small [21K]. In order to truly represent scattering and radiative transfer by coal particles, a theory is required taking into account both the structure and the irregularities of coal particles [4K]. A method developed for determining the gray gas weighting coefficients for gas–soot mixtures from the coefficients which separately model the soot behavior and the behavior of the gray gases is accurate over wide ranges of temperature, path length and soot concentration [15K].

A Monte Carlo simulation is described for studying radiant transport through an adiabatic packed bed or porous solid [1K]. The results of radiative transfer studies in suspensions of 11 μm diameter latex particles using 0.6328 μm He–Ne laser light have direct application to the design of packed fluidized bed systems wherein thermal radiation is a significant heat transfer mode [6K]. Temperature profiles, total emissivity flux density distribution, and effective mean penetration distance have been determined from radiant heat transfer studies in high-temperature solar fluidized beds [17K].

A model designed and coded for application to radiative transfer in three-dimensional vegetative systems has been applied to a soybean row crop. The simulated directional reflectance data correspond well in gross trends with the measured data [29K]. A simple radiative transfer model has been used for establishing relationships between canopy biomass and reflectance which is of interest in agricultural remote sensing [42K]. In studies of i.r. thermography, calorimetric and radiation balance equations for an object in thermal equilibrium with its environment are combined to yield a graphic interpretation of exitance as a function of surface temperature, emittance, and background factors [47K].

A two-temperature i.r. pyrometer is suitable for monitoring the rapid heating of materials. The instrument covers a temperature range from 600 to 3000 K in approximately 100 ms with a spatial resolution of 1 mm and with an accuracy of a few percent [5K]. Infrared radiation has been used for sensitizing or desensitizing silver halide films for subsequent pulses of visible light [39K]. Physical properties of heat transfer sensors may be determined from vacuum heat loss observations [11K]. Infrared emission spectroscopy is a feasible technique over both a wide frequency and a large temperature range as illustrated by some experimental results [53K]. There is excellent agreement between CARS data and corrected thermocouple temperature measurements in diffusion flames in regions of relatively constant temperatures [14K].

The temperatures measured by the two-line fluorescence technique in plasmas are accurate to 3–5% and exhibit low random error [37K]. A semianalytic Monte Carlo radiative transfer model provides the framework for probing areas of uncertainty in laser fluorosensor performance [43K].

A simpler, semianalytical formulation for radiative view factors from a sphere to a class of axisymmetric bodies requires a simple numerical integration at most [10K]. A simple double-integral expression is derived for the diffuse radiation view factor between two parallel cylinders of finite length [26K]. A general formulation is developed for the radiation shape factors between a disk and a class of coaxial axisymmetric bodies such as a cylinder, a cone, an ellipsoid, and a paraboloid [40K]. It is shown that finite elements are quite versatile for calculating view factors for radiative heat transfer if extremely irregular geometries are involved [9K].

Simultaneous measurements of the emittance and electrical resistance of thin films (2000 Å) of Ni and stainless steel sputtered onto glass tubes have been made for a temperature range from 60 to 440°C [52K]. An interferometric method for the analysis of thin films has been extended to the i.r. region providing information on thickness, refractive index and absorption coefficient of a single layer [3K]. A twin-slope method for measuring the specific heat and coating absorptance of solid materials is based on monitoring of the heating and cooling rates of a sample irradiated with a standard lamp [25K]. Austenitic steels have a higher reflectance than the ferritic and martenistic steels, but their integrated solar reflectance of 68% is considered to be too low for solar reflectors [27K]. Equations are derived for analyzing the thermal effect of radiation on semiconductors and metals with sudden changes of the optical properties [20K].

Experimental and analytical studies are reported of the characteristics of heat transfer in a semi-transparent, laminar fluid flowing in an open channel which is heated uniformly by a radiant heat source from above [23K]. Experimental results on heat transfer augmentation by use of wall radiation for an annular channel where air flows between the inner tube with uniform heat input and an insulated outer tube are in good agreement with analytical predictions [55K].

The effect of a concentric radiating cylinder on liquid spray cooling of a hot gas discharge such as a product of combustion in a gas turbine is studied for a wide range of parameters [22K]. Studies of the effect of i.r. radiation on oriented polymer fibers and polymer fabrics show that the efficiency of radiative heating depends to a large degree on the direction of the incident radiation [31K].

Analytical studies of the effects of scattering of radiation within the medium, boundary surface reflectivity and initial optical thickness of the medium on the conversion occurring in a batch photochemical reaction in plane-slab geometry indicate that scattering reduces the conversion and tends to increase the uniformity of the distribution of the reactant within the medium [45K]. A comparison of experimental data with analytical results of radiant heat transfer in high-temperature furnaces shows satisfactory agreement [30K]. For freely radiating surfaces, the cooling power at ambient temperature lies between 58 and 113 W m^{-2} for different surfaces and model atmospheres [13K].

MHD

There is continuing interest in MHD related heat transfer, especially in connection with MHD generators.

The High Performance Demonstration Experiment (HPDE) in the field of MHD generator development produced 23 MW Faraday power at 9% enthalpy extraction efficiency using cold electrodes [3M]. Work is in progress to demonstrate that an MHD generator, simulating a commercial scale device, can convert 15% of the available thermal energy into electrical power [13M]. Experimental data derived from the HPDE facility for various electrical and gas dynamic variables are in good agreement with analytical predictions [4M]. Studies of the thermal behavior of capped vs solid frame electrodes in a coal-fired MHD generator show much lower heat fluxes on the capped electrodes as compared to the solid frame electrodes [5M]. Analytical studies of the same coal-fired MHD generator show that a quasi-three-dimensional code gives an excellent matching to experimental generator performance [6M]. The three-dimensional flow and heat transfer development in an MHD channel has been studied by solving the governing equations for the coupled electrical and flow fields [14M].

Studies of mass transfer and free convective MHD flow past an accelerated vertical porous plate show that the velocity increases when the modified Grashof number increases [9M]. Studies of the effect of Hall currents on MHD flow and heat transfer between two parallel porous plates indicate that in the absence of Hall currents, the change of the direction of the applied magnetic field does not affect the primary flow [1M].

Investigation of the effects of Hall current on Couette flow and heat transfer of a conducting fluid between two plates in a rotating system show that the role of each parameter on heat transfer is always opposite to its role on shear stress [7M]. The ADI method is most suitable for calculating the temperature distribution for steady MHD axial flow through a rectangular pipe with a discontinuity in the wall temperature [12M]. Experimental studies of local properties and heat transfer of Hg–Ar two-phase bubbly flow with small gas flow rate in a vertical annulus in the presence of a transverse magnetic field show that the two-phase Nusselt number decreases as well as the single phase Hg heat transfer with increasing Hartmann number at a fixed Péclet number [8M].

Nonlinear magnetic convection is studied for small Prandtl numbers using the modal equations for cellular convection [10M]. Studies of the effect of a magnetic field on heat flow in a gas in an intermediate pressure range indicate that the special features of the Senftleben–Beenakker effect observed with decreasing pressure arise not only due to spherically symmetric molecule–surface interaction, but also due to nonspherical scattering on walls [2M]. The effects of thermal radiation, the magnetic field strength, the finite electrical conductivity and the initial wave front curvature on the nonlinear breaking of modified magneto-gas dynamic waves are discussed [11M].

NUMERICAL METHODS

Since numerical methods are used for a variety of heat transfer problems, papers reporting the 'application' of numerical methods to specific physical problems are listed in the category pertaining to the problem. The literature cited in this section is primarily concerned with the development of new numerical techniques or with the evaluation of alternative methods.

The numerical methods for the solution of the heat conduction equation in curvilinear nonorthogonal coordinates are given a physical interpretation [15N]. An efficient sequential algorithm has been developed for the nonlinear inverse heat conduction problem [2N]. The use of the ADI methods for the polar coordinates is discussed [3N]. Solution of thermal problems by the boundary point least squares method is examined [11N]. An efficient algorithm is proposed for nonlinear heat transfer with phase change [14N]. Finite elements in time and space coordinates are used for heat conduction problems [21N]. Reference [18N] describes a splitting scheme for solving the heat conduction equation in cylindrical coordinates. The stability of mixed time integration schemes is examined for unsteady thermal problems [8N]. An artificial intelligence system called KNOWTRAN has been proposed for solving heat transfer problems [17N]. Optimal finite-analytic methods have been described [9N]. Reference [6N] establishes relationships between the truncation errors on uniform and nonuniform meshes. The use of a finite-element model for the Dirichlet boundary conditions in the Laplace equation is discussed [24N]. Self-adaptive solution algorithms are proposed for nonlinear heat conduction [12N]. The conjugate-gradient method is used to develop accurate integration formulas for unsteady heat conduction [23N].

New finite-difference schemes have been developed for parabolic differential equations [10N]. Numerical techniques are described for radiation heat transfer in participating media [16N]. A free convection flow is calculated by the finite-element method [4N]. In ref. [5N], the vorticity–velocity variables are used in obtaining numerical solutions for two-dimensional Navier–Stokes equations. A numerical method is proposed for the transonic cascade flow [22N]; the method is presented as thermodynamically consistent.

The representation of the combined convection and diffusion flux and the associated matter of false diffusion are given attention in several papers. An 'upwind' finite-element method is proposed via numerical integration [13N]. Reference [19N] presents a performance comparison of many methods for a standard convection–diffusion problem; the paper includes a commentary on the solutions submitted by a large number of researchers using different methods. An error analysis is performed for the finite-element method applied to convection–diffusion problems [1N]. Reference [7N] proposes boundary-layer refinements in convection–diffusion problems, while these problems are simulated in ref. [20N] by the influence schemes as well as standard finite-difference schemes.

HEAT TRANSFER APPLICATIONS

Heat exchangers and heat pipes

Heat transfer augmentation by proper roughness of the heat exchanger surface was studied, especially in the

Soviet Union. Tubes with internal ridges generated by electrochemical etching is claimed to reduce the heat exchanger volume by a factor of 2.5 [9Q]; whereas periodic grooves on the tube surface effect a reduction of 30–50% [8Q]. The enhancement of heat transfer from a tube bundle in turbulent axial flow by spacer grids was studied experimentally [2Q]. The use of tubes with fins enhances heat transfer in film condensation as demonstrated by experiments with Freon 12 [3Q]. A microroughness parameter determines enhancement or suppression of nucleation in heat exchangers and steam generators [1Q]. The use of helical tubes in heat exchangers results in an appreciable increase in heat transfer and a corresponding reduction in heat exchanger dimensions [7Q]. Prediction equations describing heat transfer augmentation in rod bundles by grid spacers are compared with experimental results [17Q]. Swirling spacers are also considered. Evaporative cooling has been found to be the utmost heat transfer augmentation [12Q]. Experiments show that the performance of plate-fin and bare tube condensers can be predicted reliably. Experiments clarified contradictions found in data reported in the literature on the effect of pulsating flow in steam–water heat exchangers at Reynolds numbers between 500 and 2200 [10Q]. A multidimensional numerical model to predict the performance of shell and tube liquid-metal heat exchangers was developed and the results are compared with test data [14Q]. Steady laminar forced convection heat transfer in a spherical-annulus heat exchanger with water flowing on both sides was studied at Reynolds numbers between 41 and 465 by numerical analysis and by experiments [15Q].

Optimizations of heat exchangers with respect to construction cost, operating cost, or pay-back time are compared with the help of a new diagram [13Q]. A computer code developed for the optimization of air cooled heat exchangers should be a useful tool for heat exchanger design [6Q]. An enhanced tube heat exchanger for boiling of ammonia on the shell side and sea-water flowing on the tube side is considered for a case study of performance benefits and cost effectiveness [16Q]. A size reduction of 55–67% relative to a plane tube exchanger was made possible by the use of a porous surface on the boiling side.

An explicit procedure for the design of balanced regenerators has been developed [11Q].

The shut-down characteristics of an axial-groove heat pipe as thermal diode are determined by experiments and analysis [4Q, 5Q]. The shut-down times were found to depend on the shut-down power.

General

An analytical model simulating the cooling air flow in gas turbine components is discussed and compared with static bench tests [13S]. The heat flux and pressure at the end wall region and on the shroud in a turbine stage were measured with thin film heat transfer gages [7S]. The effects of the Mach number, Reynolds number, inflow angle, and turbulence level were measured on a gas turbine rotor blade in a piston tunnel using thin film gages [5S].

The time variation of the local heat flux through various parts of the combustion chamber wall were measured on a pre-chamber diesel engine [19S]. The heat flux was mainly affected by the jet flow from the pre-combustion chamber. It was also primarily influenced by the engine speed and the volumetric efficiency [1S]. The highest heat transfer occurred near the stoichiometric mixture [2S]. An increase of the volumetric efficiency from 40 to 60% resulted in an increase of the peak heat flux of 30%.

Heat transfer from the combustion gases to a single row of closely spaced tubes of a Stirling engine heater was significantly enhanced by a swirling cross flow [3S].

An analytical model predicts the temperature field in a sodium heated steam generator under oscillation induced at the critical heat flux [14S]. The model is based on the postulate that wet regions are swirling around the tube circumference.

Screening criteria were developed for the selection of fluids for long-distance heat transmission [18S]. Dowtherms, therminol, and water were considered among others. The transient heat transfer characteristics were studied by analysis and experiment for a vertical porous heat storage system imposing a constant heat flux through one wall whereas the other wall is insulated [12S]. It was found that natural convection strongly enhances the time for the approach to quasi-steady state. A similar study comes to the conclusion that a predetermined time for approach to steady state can be achieved by a proper combination of the properties of the porous medium and the dimension of the storage container [11S]. A two-phase heat transfer model simulates heat storage systems using a packed bed [17S].

Two papers are of interest for fire prevention. Experiments investigated the dynamics of smoke filling the upper hot air layer in a series of two or three rooms connected by open doorways [6S]. A numerical parametric study of the response of building components to a fire agree essentially with earlier dimensional and approximate analyses [10S].

Experiments determined the drag and heat transfer coefficients of climbing or horizontal thin films of an evaporating liquid as found in desalination plants for sea water [15S]. The real equilibrium temperature and the instantaneous cooling rate are determined for preheated river water [9S].

Heat transfer studies show that two temperature maxima can occur in large geologic repositories for spent fuel from nuclear reactors, one after 60 and one after 13 000 years [4S].

Regular arrays of heated areas arranged on a flat surface occur in electronic computers. Experiments clarified the heat transfer and pressure drop characteristics of such arrays of rectangular modules inserted into a flat wall forming one side of a rectangular duct with cooling air flowing through the duct [16S]. The effect of missing modules on the heat transfer of neighboring modules and heat transfer enhancement by protruding bars were especially investigated.

Experiments and analyses studied the thermal response of a human thigh exposed to diathermy treatment with cooling dependent on the blood flow rate [8S].

Solar energy

Calibrated terrestrial solar spectra data are presented in order to satisfy two objectives: to provide spectral data of high enough resolution and on a broad enough wavelength scale to make the data useful for studies where spectral position and band width are critical factors; and to provide in one location sets of spectra that illustrate several atmospheric effects on the solar spectrum [3T]. A series of total and spectral solar irradiance measurements were made on the ground (Table Mountain Facility, California, altitude 2.18 km) and the spectral data are presented for the 0.3–3.0 μm range for air mass 1.5 [27T]. The simultaneous measurement of solar radiation at several angular positions is accomplished with a newly designed multidirectional photodiode array [9T]. Hourly pyrheliometer and pyranometer data from four U.S. locations are used to establish a relationship between the hourly diffuse fraction and the hourly clearness index [10T]. The performance of models to estimate solar irradiance and its components is assessed using data for six Canadian stations for nine years [8T]. Four methods of estimating hourly diffuse irradiation from hourly global irradiation are compared, using global and diffuse irradiation data from five widely separated locations [38T]. An analytical solution is presented for the calculation of monthly average insolation on shaded surfaces at any tilt and azimuth [36T]. The annual average solar radiation incident on a variety of principal solar collector types, including shading effects, is calculated by approximating the annual variation of daily radiation by its value on one average day, equinox [13T]. A model for clear-day solar irradiance for a specific site is presented in a simple format utilizing parameters based on readily available long-term daily global irradiance data and the model results are found to be in excellent agreement with observations [21T]. A new empirical formula has been developed which permits the determination of equivalent nocturnal sky emissivity as a function of the site's altitude, ambient temperature, relative humidity and the degree of cloudiness, mist or haze present at the time [4T].

A fairly simple technique has been developed to calculate monthly utilizability or monthly collection efficiency for solar thermal collectors and the heart of the technique is an empirically determined performance map that provides quick evaluations of changes in collector design, geographic location, and collector inlet temperature [11T]. An explicit nonlinear model which predicts the performance of a solar collector, including effects of radiative losses, was obtained from the empirical correlation of simulation data from a total of 3969 separate computer simulations which included 50 different collector designs and a wide range of operating conditions [30T]. A survey is presented of the work done at the University of Melbourne with regard to the effectiveness of the insertion of a honeycomb structure into the air gap between the absorber plate and the cover of a flat-plate solar collector in order to suppress convection [15T]. The operation of a conventional solar air heater with two covers in a two-pass mode offers an inexpensive method of improving collector efficiency by about 10–15% [40T]. The energy absorbed by two types of tubular solar receiver elements were analyzed: (a) an inner tube with an absorbing coating surrounded by a semi-transparent cover tube, and (b) a semi-transparent inner tube filled with an absorbing fluid surrounded by a semi-transparent cover tube [34T]. Wind tunnel experiments were carried out to determine forced convection heat transfer coefficients for the leeward face of a roof-like structure [37T].

A comparison of the gain that can be achieved with a one- or two-stage concentrator, when the first stage is a Fresnel lens or parabolic mirror, shows that the achievable gain using a parabolic mirror is greater than that obtained using a flat or roof lens but is lower than that obtained using a curved lens [23T]. The conditions for achieving ideal and Lambertian symmetrical solar concentrators are analyzed [24T]. A general procedure for determining the optimum geometry of a reflector-augmented solar collector which produces a desired pattern of flux-augmentation is described [5T]. Natural convection heat transfer coefficients have been experimentally determined for trough-type collectors [28T].

The transmittance of unpolarized light through a solar collector cover made of cylindrical glass tubes in a coplanar parallel close-packed array is dependent on the orientation of the cylindrical axes of the tubes in the plane of the cover [16T]. A new apparatus that incorporates an integrating sphere is described which enables the solar transmittance of test samples to be measured as a function of both angle of incidence and azimuth angle [39T].

A mathematical model for simulating the dynamic temperature response of a packed column to an arbitrary time-dependent inlet air temperature is used to optimize heat storage in a rock bin system subject to a realistic transient inlet temperature [33T]. A general method for solving the differential equations describing the heat transfer process within a rock bed is presented and a numerical model accounting for secondary phenomena such as thermal losses and conduction effect is developed [7T]. A preliminary model for estimating possible thermal energy storage in a phase change shell and tube heat exchanger is presented [35T]. A comparison is made of three models for analyzing the thermal behavior of a paraffin wax thermal store powered by a liquid-type heat transfer fluid [26T]. An experimental study of the temperature decay in a thermally stratified water body with various initial temperature distributions indicate that the temperature field is largely one-dimensional [20T]. In a two-part paper, axisymmetric natural convection flows in a thermocline-type cylindrical enclosure are studied experimentally with a laser-Doppler velocimeter [17T] and a numerical model was developed using these experimental data [18T]. The effects of storage tank stratification on the instantaneous performance of a liquid-based solar heating system are presented in terms of a stratification coefficient which is shown to be a system constant that depends on only two dimensionless system parameters [31T].

After summarizing the methods for calculating the solar contribution for systems without thermal storage, this paper extends a previously proposed method which is based on using a frequency distribution of solar flux data [12T]. Using analytical methods it is shown that the effects of transition times of fluids in collector arrays and system piping on energy collection in solar systems with well-mixed storage tanks can be accounted for by a reduction factor multiplying the collector heat removal factor, F_R [41T]. The problem of nonuniform flow distribution on the thermal performance of solar collectors is treated and a method of determination of the deterioration of the collector efficiency due to the flow nonuniformity is developed and presented [6T].

A recently-developed analytic model for predicting passive solar heating performance is applied to the case of selective coatings on storage walls [14T]. Flow visualization studies on laboratory models of Trombe walls have given a deeper insight into the fundamental flow mechanisms, while air velocity and temperature measurements have been used to explore the natural convection heat transfer processes involved in the thermocirculation flow [1T]. The monthly-average auxiliary energy requirements of a building with a Trombe wall is estimated using upper and lower theoretical limits to system performance and an empirical correlation is presented for the fraction of the load met by the Trombe wall for systems with finite capacity [29T]. A paraffin Trombe wall with double glazing is studied experimentally with the help of a test-cell allowing several working conditions to be checked [2T]. Numerical studies were performed of the daily temperature fluctuations in a direct gain room [25T].

Events that induce or inhibit mixing layer development in a thermohaline system are simulated in laboratory experiments involving salt-stratified solutions heated from below, cooled from above and/or irradiated from above and a Mach–Zehnder interferometer was used to visualize mixing layer development [22T]. Calculations indicate that decreasing the reflectivity of the bottom of a solar pond from 0.20, typical of dirt, to 0.05 significantly increases pond thermal efficiency [19T]. A numerical calculation of the heat and mass transfer in solar stills is reported [32T].

PLASMA HEAT TRANSFER

Plasma heat transfer continues to attract interest, in particular in the areas of arc technology and plasma processing.

Experimental and analytical studies of the recovery of an axially blown SF_6 arc after zero current indicates that the temperature change is determined by flow turbulence and deviations from LTE have also some effect on the shape of the recovery curve [2U, 18U, 22U]. Experimental studies of a SF_6 arc plasma at atmospheric pressure indicate that there is collisional equilibrium for sulfur and demixing has a negligible effect on the plasma state for the chosen conditions [26U]. Investigations of the mechanisms for temperature decay in a freely recovering gas blast arc indicate that axial convection tends to heat the arc channel downstream of the stagnation region in both N_2 and SF_6. Radial convection is a dominant cooling mechanism for both N_2 and SF_6 [20U].

Measured isotherms in the vicinity of a thermionically emitting (thoriated W) cathode in a high intensity, atmospheric pressure argon arc reveal temperatures up to 26000 K and temperature gradients in excess of 8.7×10^{3}°C mm^{-1} [1U]. A hot cathode arc discharge can be initiated with an auxiliary discharge which heats the cathode to the required temperatures [11U]. Using a Cu–W cathode in a pulsed free-burning arc (12.5 kA) at atmospheric pressure, the vapor supply from the cathode seems to eliminate the usually observed pumping action in the vicinity of the cathode and the associated enthalpy transport to the anode [28U].

Electrode heat transfer in vortex-stabilized arcs for both DC and AC operation is a linear function of the current and in the case of AC, electrode heat transfer is approximately half of the heat load measured at the anode of a DC arc under similar conditions [5U]. Anode spot formation in vacuum arcs is closely linked to anode melting and possibly to magnetic deformation of the molten surface. This lends support to the conjecture that localized heating of the anode can trigger spot formation [8U].

The application of the conventional multitemperature Saha equation to high pressure plasma at temperatures (heavy particles) below 8000 K may lead to substantial errors [19U]. Experimental and analytical studies of deviations from kinetic equilibrium in a decaying, atmospheric pressure argon arc plasma show that spectral line intensity measurements provide reliable data for the gas temperature [7U]. The temperature of a high-pressure gas discharge may be determined from the total intensity of a self-reversed spectral line if the plasma is in local thermodynamic equilibrium [9U].

A relatively simple method is presented by which the amount of self-absorption in laboratory-produced plasmas can be evaluated [17U]. A new electro-optical technique for measuring temperatures in thermal plasmas is based on the determination of the variations in the outputs of a two-wavelength pyrometer which views a small section of the plasma [15U]. A computer-controlled spectrometric system for measuring temperatures in thermal plasmas is particularly useful if fast scanning is necessary or desirable [6U].

Recent developments are reviewed associated with the extraction and refining of metals using thermal plasmas as the heat source [12U]. The two major heat transfer components in a nitrogen transferred arc, resembling an arc furnace, are enthalpy transport by the electrons to the anode and radiative heat transfer from the arc column [25U]. Theoretical and experimental investigations confirm that a hybrid plasma torch, in which a rf plasma is superimposed to an arc jet, is an effective reactor for the preparation of ultra fine refractory compounds [24U]. Comparisons of predicted and measured temperature and velocity fields in thermal plasma jets reveal good overall agreement. Radiation has a small effect on the overall heat transfer process [14U].

Evaporation severely reduces heat transfer to a particle exposed to a thermal plasma and, in general, this effect is more pronounced for materials with low latent heat of evaporation [3U]. Studies of the unsteady heating of small particles in thermal plasmas show that evaporation (or sublimation) is by far the slowest step among all the processes taking place in a plasma reactor [4U]. Experimental and analytical studies of the heat and momentum transfer to particles injected into a thermal plasma jet (plasma spraying) reveal good agreement between predicted and measured particle velocities. There is, however, a discrepancy between predicted and measured surface temperatures of the particles [27U]. An experimental study of the thermodynamic parameters, optical properties and heat transfer from a thermal plasma produced by reflection of a shock wave from a plane surface indicates that adding of solid particles to the air reduces the heat flux density at velocities in excess of 5 km s^{-1} [10U].

A reactive plasma process proved to be successful for the preparation of solar grade silicone. With this plasma zone melting technique, the iron content was, for example, reduced from 3500 to 0.5 ppm at displacement rates from 20 to 40 cm h^{-1} [16U]. When a mixture of Nb_2O_5 and B is heated in a thermal argon plasma to approximately 3000°C and subsequently annealed at approximately 2000 K, a superconducting NbB_2 is formed with a transition temperature $T_c > 4$ K [13U]. Hydrogen peroxide (H_2O_2) may be produced by dissociating water vapor in a rf discharge. Heating of the rf plasma and its spatial afterglow from 25 to 600°C has little effect on the percentage of H_2O dissociation and on the formation of H_2O_2 [21U]. A supersonic beam of atomic oxygen is produced by using a conventional plasma torch as the heat source. Dissociation efficiencies approaching unity are achieved with beam velocities in the range of 1.5–4 km s^{-1} [23U].

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