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Heat transfer—a review of 1983 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 1983. 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 sessions on heat transfer have been held during 1983.

An International Symposium Workshop on Renewable Energy Sources held March 18–22 at Lahore, Pakistan was presented by the Clean Energy Research Institute of the University of Miami, Florida. Heat transfer had to be considered in many of the papers dealing with various forms of energy utilization.

A Thermal Engineering Conference in Honolulu, Hawaii was organized jointly by the American and the Japanese Societies of Mechanical Engineering and held March 20–24. Heat transfer topics dominated the sessions which dealt with all of the modes of heat transfer and with heat transfer applications, especially with heat exchangers. Keynote lectures were presented by P. J. Marto on "heat transfer and two-phase flow in shellside condensation", by K. E. Torrance on "boiling in porous media", by J. R. Lloyd on "separated forced convection", by K. Nishikawa on "boiling heat and its augmentation" and by G. M. Faeth on "recent advances in modeling particle transport properties and dispersion". A round table discussion was concerned with prospects for advanced open and closed Otec cycles. A number of sessions considered heat and mass transfer in underground media and in geothermal applications. Four short courses rounded out the program. The papers are available in four volumes through ASME and JSME.

The 28th International Gas Turbine Conference and Exhibit included in its program sessions on film cooling, turbine gas path heat transfer, and closed cycle gas turbine heat exchangers. Technical papers are available through ASME Headquarters.

The Third Multiphase Flow and Heat Transfer Symposium was held during April 10–20 at Miami Beach, Florida organized by the Clean Energy Research Institute of the University of Miami. It included sessions on heat and mass transfer, scale formation in boiling and various applications.

The 21st National Heat Transfer Conference sponsored by the American Institute of Chemical Engineers and the American Society of Mechanical Engineers was held at Seattle, Washington on July 24–27. The sessions were primarily organized according to the heat transfer modes but included, in addition, sessions on applications, for instance, analysis of steam generators, heat transfer in drying systems and in fusion energy systems. The topic "waste heat recovery" was considered in a round table discussion. Short presentations could be offered in an open forum. The papers presented at the conference are available as preprints or in the published series of the American Institute of Chemical Engineers. Many will also be published in the *Journal of Heat Transfer*. Invited lectures were given by J. G. Knudsen on "Fouling of heat exchangers—how we solve the problem" and by S. Ostrach on "Recent developments in transport phenomena". Both researchers also received the Donald Q. Kern Award and the Max Jakob Award respectively.

An International Conference on Energy Efficient Buildings with Earth Shelter Protection brought together an international group of experts in Sydney, Australia on August 1–10. Proceedings were published by Oklahoma State University.

Heat transfer in porous media was included in the sessions of the 20th Annual Meeting of the Society of Engineering Science at the University of Delaware, August 22–24.

The 15th Symposium of the International Center for Heat and Mass Transfer held at Dubrovnik, Yugoslavia, September 5–9, 1983 was devoted to heat and mass transfer measurement techniques.

The 1983 Tokyo International Gas Turbine Congress was organized by British, German, Japanese and American Engineering societies and held at Tokyo, Japan, October 23–29. Heat transfer was the topic of five sessions considering external, internal, and unsteady heat transfer, film cooling, and heat exchangers.

The Mechanical and Aerospace Engineering Department of the University of Tennessee and the National Bureau of Standards organized a course on Multi-component Condensation and Boiling at Gaithersberg, Maryland, November 8–10.

The Winter Annual Meeting of the American Society of Mechanical Engineers held at Boston, November 13–18, included 19 sessions dealing with various topics of heat transfer. Two symposia considered advances in the cooling of microelectronic devices and in electronic packages. A panel discussed advances in regenerator design and technology. A keynote address by C. L. Tien dealt with "recent advances in thermal insulation". J. Kestin discussed "false and creative fascination with accuracy" as the speaker at the heat transfer luncheon. E. R. G. Eckert selected the topic "experiments on energy separation in fluid streams" for the Thurston lecture. The Heat Transfer Memorial Award was presented to R. Eichhorn. Preprints of the papers are available at ASME Headquarters and many of the papers will also be published in the *Journal of Heat Transfer*.

The Third International Conference on Numerical Methods in Thermal Problems was held in Seattle, Washington, August 1–3, 1983.

Two journals on heat transfer were started in 1983. The *International Journal of Heat and Fluid Flow*, published quarterly by Butterworth Scientific—Journals Division, Guildford, Surrey, U.K., will include papers on engineering thermodynamics, heat transfer, and fluid dynamics together with measurements techniques and applications. The journal *Heat and Technology* was launched in August of 1983 and is published quarterly by Pitagora Editrice, Bologna, Italy. It will include basic and applied research in heat transfer and fluid mechanics and emphasize numerical, industrial and technical applications. A journal *Drying Technology*, published by Marcel Dekker, New York, should also be of interest to the heat transfer community.

The following highlights illuminate developments in heat transfer research during 1983.

Papers on channel flow considered complex thermal boundary conditions, conjugate heat transfer, non-Newtonian behavior, variation of fluid properties, and influence of buoyancy. Many of the configurations studied have relevance to heat transfer augmentation devices, compact heat exchangers, and cooling of electronic components. Experimental results were published on heat transfer to groups of cylinders and spheres, cavities, and tube banks. Thermal convection in saturated porous media filling containers of various shapes were treated analytically, whereas experiments were used to study heat and mass transfer in unsaturated media, including boiling, and in fluidized beds. Natural convection was studied for various flow conditions ranging from laminar steady to turbulent transient flows and for constant and variable properties.

Boiling heat transfer and the related conditions of two-phase flow continue to be areas of active research. The motivation for this research appears to be increasingly diffuse with studies directed towards cooling of nuclear reactors composing a diminishing but still major fraction of the literature. Investigations of critical heat flux [CHF] phenomena were reported and interest is evident in fundamentals of nucleate boiling including transient phenomena, boiling of mixtures, and fouling of heat transfer surfaces. The most frequent topic in condensation heat transfer in 1983 was film condensation, including studies evaluating various fin geometries and determining the effect of the interfacial waviness. A notable omission is the submerged vapor jet in a subcooled liquid pool, a frequent topic in last year's review.

A large number of papers presented calculation methods for radiative interchange in systems of gases, fluids, and solids including radiation–convection interaction. Methods to measure radiative flux and properties were described and applications included fibrous insulation and fluidized beds. Interest in MHD heat transfer has strongly decreased.

In the field of heat transfer applications, manufacturing processes have found increasing attention. The flights of the space shuttle provided the opportunity to check established procedures for the prediction of heat transfer in aerodynamic heating. Papers dealing with the solar energy application included predictions and measurements of the availability of solar radiation, the performance of flat plate solar collectors, and heat transfer in passive solar energy applications.

A growing number of papers on plasma heat transfer testify to the increasing importance of this field. They include particle heat transfer which is important in plasma chemistry and processing applications.

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

- Conduction, A
- Channel flow, B
- Boundary Layer and external flows, C
- Flow with separated regions, D
- Heat transfer in porous media, DP
- Natural convection—internal flows, F
- Natural convection—external flows, FF
- Convection from rotating surfaces, G
- Combined heat and mass transfer, H
- Boiling, J
- Condensation, JJ
- Freezing and melting, JM
- Radiation, K
- MHD, M
- Applications
  - Heat exchangers and heat pipes, Q
  - General, S
  - Solar Energy, T
  - Plasma heat transfer, U

CONDUCTION

The focus of the published work on conduction is contact resistance although other areas such as solution techniques and applications to various geometries are included.

Some work on fundamentals has been published including an application of irreversible thermodynamics to develop the theory of heat conduction [23A]. A property related to entropy that must decrease with time has been found that can be applied to solutions of the transient heat conduction equation [9A]. Classic heat diffusion theory was shown to underestimate the temperature and heat flux at a thermal front at short time intervals from the start of a thermal pulse [35A].

Various innovative solution techniques have been proposed. The use of the Chebyshev collocation operator for the heat equation was given with several mathematical proofs [14A]. Solution methods were also described for transient nonlinear heat conduction with absorption [21A]. Approximate solutions for parabolic nonlinear heat conduction problems were given [7A]. A fast approximate solution technique was developed for multi-dimensional transient problems with variable conductivity or specific heat capacity [5A].

A solution for a 2- or 3-layer composite slab with three boundaries insulated was given in a pair of papers [28, 29A]. Solutions to transient heat flow through a composite slab is useful in simulating the thermal performance of building walls. A fast root-finding technique for this problem was given [15A] that would help to determine the response factors used in practice. The smoothing of temperatures near the boundaries of a composite cylinder was used to remove short-circuiting phenomena that can appear in solutions [36A]. Treating a composite material as if it were homogeneous may simplify the solution procedure provided correct values for macroscopic conductivity and heat capacity are known [1A]. Numerical solutions were obtained for a slab penetrated by metal rods that behave as fins [17A]. A boundary integral method was used to compute the effective conductivity of an array of spheres embedded in a matrix in either a body-centered or face-centered cubic configuration [38A].

The steady heat flow through 1-D anisotropic, inhomogeneous solid was given using a boundary integral method [8A]. Two- and three-dimensional steady conduction through anisotropic materials was studied using a coordinate transformation [16A].

Contact resistance continues to pose challenging problems in a variety of applications. A crack in an elastic half-space produces a 2-D static thermal problem with radiative heat transfer through the crack [12A, 13A]. The contact resistance between two slabs changes with time if one of the slabs contracts as it cools [18A]. The conductance of materials used in reactor fuel rods is important to predict rod temperatures and to correlate experimental data [25A]. Fuel-cladding conductance has been analyzed using acoustic mismatch theory [10A] and simulated using a Kalman filter [34A]. The effect of a penney-shaped crack on the heat flow and local stress has been considered both within a solid [31A] and at the interface between two solids [26A, 2A]. A comprehensive mathematical treatment of steady heat flow through a thin, poorly conductive layer was presented [4A].

Measurement of the effective thermal conductivity of moist, capillary-porous bodies including phase change was described [37A]. The radiation errors encountered when measuring conductivities at cryogenic temperatures were analyzed [24A]. Corrections and improved measurement techniques were described. The development of an instrument to measure the thermal conductivity of an arbitrary shaped solid was given [20A]. A transient probe technique was described for measuring effective conductivity and specific heat in soils [19A].

Numerous applications have been considered, primarily for steady heat flow in particular geometries. The temperature distribution in an electrically heated thin foil shows that the foil does not provide a uniform heat flux as commonly assumed in experimental studies [32A]. The discrepancy was attributed to electromagnetic field variations. An optimum cylindrical pin fin was identified that includes a convective coefficient that is fin diameter dependent [22A]. A bicylindrical coordinate system was utilized to obtain a solution to steady conduction through an eccentric annulus with convective boundary conditions [11A]. A boundary integral method provided solutions to steady heat flow from a row of cylinders embedded in either a half-space or a homogeneous slab [6A]. Handbook solutions to this problem were shown to be in error by as much as 20%. A solution method to determine the optimum location of a fixed amount of insulation distributed on the surface of a 2-D conducting body was given [3A]. Numerical results were presented for a rectangular slab. A related study was performed in which exergy production in two parallel insulation systems is minimized [30A]. Transient internal heating due to torsional damping was analyzed to explain the premature failure of generator rotor shafts [27A]. Transient 1-D conduction with variable properties and internal heating was studied to simulate the thermal performance of salt gradient stabilized solar ponds [33A].

CHANNEL FLOW

Internal flows have been studied in simple configurations such as the circular tube or parallel plates and also in complex passages encountered in heat transfer augmentation devices. The flow conditions include laminar and turbulent regimes, single-phase and multi-phase systems, and Newtonian and non-Newtonian behavior. Both steady state and transient flows have been investigated.

The effect of viscous dissipation has been analyzed for the thermal entrance region in laminar pipe flow [30B]. Reference [18B] considers laminar heat transfer to Newtonian and non-Newtonian fluids. Also, high-viscosity non-Newtonian fluids are treated with different thermal boundary conditions in [16B]. A study of both heat transfer and friction in a laminar pipe flow of non-Newtonian fluids is reported in [14B]. In another investigation related to non-Newtonian flow, heat transfer to a power-law fluid is obtained at low Peclet numbers [15B].

Reference [29B] deals with liquid metal heat transfer with a uniform wall heat flux for a turbulent pipe flow. Enhanced heat transfer and the associated drag is considered for a turbulent pipe flow with a helical-wire-coil insert [41B]. The developing flow and heat transfer in a helical coil is studied in [24B], where transition from turbulent to laminar flow is included.

A number of papers focus on the unsteady nature of the duct flow. Reference [32B] considers the unsteady heat transfer in a laminar pipe flow subjected to a step change in the ambient temperature, while the response of the heat transfer to a step change in pumping pressure is dealt with in [31B]. The transient laminar heat transfer inside a circular tube is analyzed in [13B]. Experimental measurements for the flow field in an unsteady reacting nozzle exhaust flow are presented in [27B]. Reference [47B] deals with the large heat transport caused by the spontaneous gas oscillations in a tube.

Among more complex flows involving circular tubes are the studies of heat transfer downstream of an orifice [45B] and entrance heat transfer with deposit formation [46B]. A simple heat transfer model has been proposed for separated flows in tubes [10B]. Reference [26B] deals with heat transfer to gas–solid suspensions flowing downward in a circular tube, while heat transfer in a vertically upward gas–solid slug flow is considered in [5B]. Numerical solutions have been obtained for the wall temperature for near-critical para-hydrogen flow in vertical tubes [7B]. Reference [28B] provides empirical correlations for turbulent friction and heat transfer for visoelastic fluids. The Lockhart–Martinelli correlation has been discussed in [12B].

A study of convective heat transfer in a parallel plate channel with porous lining is presented in [11B]. Reference [2B] considers the effect of buoyancy in the entrance region of horizontal rectangular channels. For noncircular ducts the peripheral variation of the wall temperature is examined in [6B]. Correlations are provided in [8B] for convective heat transfer in vertical annular gas layers with constant heating from the inner wall. Reference [20B] deals with low Prandtl number convection between differentially heated end walls, while heat transfer coefficients are provided in [19B] for ducts with constant wall temperature. Thermal instability in plane Poiseuille flow heated from below has been investigated in [48B]. Reference [17B] considers the effect of the longitudinal vortex on the free and forced laminar convection between parallel plates. An experimental study of the low Reynolds number flow between interrupted flat plates is reported in [36B]. Another experimental investigation looks at the turbulent flow and heat transfer in a flat duct with maldistributed inlet flow [44B]. The heat transfer enhancement due to streamwise-periodic disturbances at one wall of a channel is considered in [42B].

The nonlinear convection in a sparsely packed porous medium has been studied by using spectral analysis [37B]. The heat transfer characteristics have been investigated for a 2-D T-shaped flow junction [25B]. Reference [34B] considers heat transfer in a parallel plate duct with circular cylinders inserted in a staggered arrangement. A study of flow and heat transfer in corrugated wall channels is reported in [22B] and [23B]. Heat transfer from concave and convex walls of a return bend of rectangular cross section is considered in [38B], [40B], and [39B].

Experimental measurements are reported for heat transfer and fluid flow in a tube fed by a plenum having nonaligned inlet and exit [43B]. In another investigation [33B], the tube heat transfer is measured for skewed inlet flow caused by competition among tubes fed by the same plenum. Reference [1B] deals with critical flashing flows in nozzles with subcooled inlet conditions. A solution for dispersed flow heat transfer is presented in [49B] under equilibrium fluid conditions. Heat transfer enhancement in an oscillatory cavity flow is studied in [4B]. Reference [21B] provides experimental measurements of heat transfer to a gaseous solid suspension. A numerical and experimental study of turbulent heat transfer downstream of a pipe expansion is presented in [3B]. Laminar forced convection heat transfer in spherical annuli is considered in [35B]. The influence of forced flow on the HeII–HeI transition has been investigated in the presence of heat transfer [9B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Laminar flows

Heat transfer measurements were made on interrupted plates aligned with the flow. The effects of leading edge bluntness, plate spacing, and Reynolds number were evaluated. The heat transfer rate of a downstream plate was higher than predicted by theory, and may be higher than that for an upstream plate [35C]. A numerical heat transfer analysis was made on a low-heat-resistance stretching sheet moving through a fluid [1C]. The transient heat transfer problem for droplet heating at high Peclet number was computed. Results showed that the transient period of internal isothermal redistribution represents a significant part of the droplet total heating period; asymptotic heating results cannot be used with good accuracy [14C]. Heat transfer in micropolar boundary layer flow over a flat plate was studied [19C]. Numerical solutions to convective heat transfer problems in axisymmetric coordinates were presented. The method used a local analytic solution to minimize false diffusion [10C]. Gyarmati's principle for the evaluation of irreversible processes was applied to stagnation flows in two dimensions [5C]. An analysis for the unsteady conjugated heat transfer problem at the 2-D stagnation point on a high thermal conductivity plane wall was presented [13C]. Heat transfer from a constant-temperature hot-film on a flat wall was computed. Measurements were taken in pulsatile and linearly decelerating flows. The thermal wake was observed in high-frequency reversing flow and enhancement of the time-average heat transfer was found with high frequency pulsatile flow [22C]. An analysis of heat transfer from a thin needle in an accelerating flow of non-Newtonian fluid was presented. The more slender needles were shown to have higher wall heat flux, with a given Prandtl number [11C]. Heat transfer solutions were found for flow of a power-law fluid over 2-D and axisymmetrical bodies, including flows with a step in surface temperature. Geometries included wedge-flows and flows over circular cylinders [23C]. Nonisothermic flows of gas mixtures in a channel at intermediate Knudsen numbers were analyzed. The dependence of the kinetic coefficients of the Onsager matrix on the Knudsen number for one-component and binary mixtures was discussed [36C]. An analysis using Fourier transforms was made of thermal waves on a flat plate in a supersonic stream. The effect of variation in the wall temperature was studied [12C]. Analytic solutions were found for nonstationary boundary layers produced by planar, cylindrical and spherical detonation waves. The Prandtl number was shown to have a significant effect on the structure [26C]. Solutions were presented for a Fredholm integral equation of the first kind, which arises in forced convection. Existence and uniqueness of the solutions were discussed [4C].

Mixed [natural and forced] convection over a horizontal plate was analyzed. Fluids with high Prandtl numbers were shown to have a wider range of conditions for mixed convection than those of low Prandtl numbers [30C].

A numerical model was presented for the conjugate problem of optimizing boundary heating of solids over a range of Biot numbers [27C]. Heat transfer from a surface coated with a thin film of high thermal resistance (e.g. paint) was analyzed. A model for an effective heat transfer coefficient for this conjugate problem was presented [9C].

Turbulent flows

Measurements of velocity and temperature profiles and momentum and heat fluxes were presented for air flow over a flat plate in the presence of an unheated starting length. Profiles of turbulent Prandtl number were deduced and support was found for a turbulent Prandtl number value of 0.9 in the turbulent core [32C]. Turbulent time scales for a thermal mixing layer were obtained via a transport equation for dissipation rates of temperature variance [16C]. Spectral relationships between velocity and temperature fluctuations were presented. The frequency dependence of a turbulent Prandtl number which is based on a shear stress and normal heat flux co-spectra was measured. Higher values of turbulent Prandtl number were associated with lower frequencies [17C]. The thermal structure of a diffusion flame was measured. Profiles of turbulence intensity of temperature fluctuations had two maxima and one minimum [34C]. A method for visualizing heat transfer was presented where "heatlines" and a "heat function", analogous to streamlines and the stream function, were used [24C].

Turbulent thermal and kinematic properties of a wake of a flat plate heated on one side were measured. Similarity coordinates were found and it was shown that profiles of Reynolds shear stress and turbulent heat transport were similar when the axes were properly oriented [28C]. Measurement of mean and fluctuating velocities and temperatures were taken in a boundary layer responding to a double step-change (up then down) in wall heat flux. Two boundary layers were identified; one for each step [3C]. Transient forced- and natural-convection average heat transfer coefficients were measured for helium flow in a channel with a step change in heat flux. For low heat fluxes, boiling heat transfer was superior to supercritical heat transfer [18C]. Heat transfer rates were measured in convex-curved boundary layers. A 50% reduction in Stanton number due to curvature was observed. Data was also presented for laminar and transitional boundary layers with streamwise convex curvature [31C]. Thermal and hydrodynamic measurements were made in an artificially thickened turbulent boundary layer on a rough surface. Mean velocity and turbulence profiles were 2-D and self-preserving. Heat transfer data showed the response to a large effective unheated starting length [25C]. Flow patterns were observed and local heat transfer rates were measured for flat-plate flow over a circular cylinder cavity. Maximum heat transfer was effected when the cavity had a depth-to-diameter ratio of 0.5 [20C]. Experimental results which show the effects of free-stream turbulence were presented. Skin friction and heat transfer increased 20% when the free-stream turbulence intensity was increased to 7% [7C]. The data was compared to existing correlations and new correlations were proposed. The effect of free-stream turbulence on the Reynolds analogy was discussed [8C].

Augmentation of heat transfer from a circular cylinder with increased turbulence created by swirl and impinging jets was measured. For a given pressure drop, impinging jet augmentation gave the greatest benefit [15C]. Heat transfer from a cylinder covered with close-fitting fabric was measured to learn the nature of wind penetration effects of clothing. Appropriate parameters were recommended [33C]. Heat transfer rates from an elliptic cylinder were measured at various angles of attack. The mean Nusselt number was shown to be higher than that of a circular cylinder [29C].

Measurements were presented for mean temperature in a nonbuoyant, heated jet issuing into a cold stream. The extra rate of strain due to streamwise curvature and longitudinal temperature gradients were shown to affect the rate of generation of temperature fluctuations. Measurements of turbulent Prandtl number indicated high near-wall values with a decline to 0.9 away from the wall [2C]. Measurements of heat transfer rates with an air jet impinging on a perforated target surface were presented. Spent air was withdrawn through the surface [21C]. Mass transfer into a turbulent liquid film was analyzed. Surface tension was shown to not affect the mass transfer coefficient [6C].

FLOW WITH SEPARATED REGIONS

Several papers considered the flow and heat transfer around groups of blunt bodies. Local heat transfer coefficients were measured [5D] on a circular cylinder exposed to flow normal to its axis with two small cylinders arranged downstream of the separation line for wake control. Results are reported at subcritical Reynolds numbers. Local heat transfer rates on two spheres arranged sidewise side-by-side and exposed to a flow normal to their axis were influenced by the formation of a jet-like flow between the spheres as shown by experiments [10D] at a Reynolds number around 10^4 and a turbulence level of 1.1%. The ratio of the distance of the centers of the spheres to the sphere diameter was varied from 1.04 to 2. At small values of this ratio, the wake was deflected sidewise resulting in crosswise force on the spheres. Heat transfer and flow patterns were also studied [12D] for two contacting spheres at various angles of attack at Reynolds numbers between 4000 to 26,000, with both or only one sphere being heated. The interaction was found largest when the spheres were in line with a heat transfer coefficient which increased at higher Reynolds numbers. A perturbation method [15D] studied transient heat transfer from a wire with constant temperature in a fluctuating environment. Maximum heat transfer was found to occur at a certain frequency. Experimental results [6D] describe heat transfer from a cylinder in cross flow of a bubbly gas–liquid mixture. Heat transfer from fuel pins in gas cooled reactors could be improved by transverse, helical, or interrupted ribs [4D].

Two interferometric studies [2D, 1D] considered laminar heat transfer downstream of a step in the surface contour or in flow over a cavity. For the downstep, the heat transfer could be described by the equation

$$\overline{St} = 0.787\,(Re_s)^{-0.55}(s/d)^{0.72}$$

where s = height of downstep, x = downstream distance from it.

In both geometries, heat transfer coefficients were less than on the plane surface. The turbulent Prandtl number profile across a plane jet was found [3D] to increase from a value 0.7 at the center plane towards 1 when approaching the border of the jet. A numerical study of wall heat transfer in the recirculating flow region of a confined jet [7D] was compared with the results of previous experiments.

Local mass transfer for cross-flow through tube banks was measured [9D] by the electro-chemical technique at intermediate Reynolds numbers. The per-tube heat transfer was also investigated [13D] in a tube bank with a constriction upstream of the tubes which created an abrupt enlargement of flow cross section. The results of experiments [D11] with an array of slabs exposed to flow normal to their plane could be described by the equation

$$\overline{Nu} = 1.19\,Re^{0.465}\,Pr^{0.375}\,(P/W)^{1/4}$$

in which P denotes the distance of the slabs and W their width. Oscillation of a grid of slabs which were parallel to the flow [8D] improved the sidewise spreading of a temperature profile in the approaching flow compared with the stationary grid. The time mean temperature profile with the shape of a probability curve approaching the grid was found to transform into a profile with two maxima downstream of the grid. The energy separation in a vortex tube was studied experimental [14D] for a range of inlet pressures. It is suggested that Goertler vortices, produced by tangential velocities in the vortex flow, are a major driving force for the energy separation.

HEAT TRANSFER IN POROUS MEDIA

Thermal convection in saturated porous media was studied almost exclusively by analysis. A number of papers considered a rectangular cavity with the vertical walls being at different temperatures or with a constant heat flux from one of the vertical walls to the other one. It was found [5DP] that the boundary layer description of the convection process is valid as long as the Darcy–Rayleigh number is large compared to $10^4 L^2$ where L is the height to depth ratio. An analysis [2DP] for constant heat flux at Rayleigh numbers between 100 and 5000 and a ratio of height to width between 1 and 10 established that the boundary layer thickness is constant along the height, the core is motionless, and the temperature gradient is also constant in the porous layer along the height in the central region. Numerical results agree with boundary layer analysis. Horizontal or vertical internal flow obstructions were found [1DP] to increase or decrease heat transfer. Several vertical layers of different permeability were studied [19DP] with regard to their influence on heat transfer. Analysis [5DP] of unsteady natural convection in the enclosure established the regions when vertical or horizontal boundary layers are formed. Three-dimensional natural convection in a cubic container with isothermal walls and internal heat generation was analyzed [4DP] for a porous medium modelling agricultural products. A numerical analysis [10DP] obtained temperature and velocity profiles as well as Nusselt numbers and established that boundary layer analysis sometimes underestimate Nusselt numbers at small Rayleigh numbers. An exact solution was obtained [23DP] for the problem to determine the shape of the coolant entrance boundary of a porous region which generates a desired distribution of the cooling along the exit boundary. A unit cell model predicts [14DP] the thermal conductivity of a granular medium containing an adhesive binder and demonstrates that the binder can increase the conductivity significantly. A transient analysis [22DP] of a packed bed thermal storage system includes longitudinal thermal dispersion and particulate conduction. The unsteady boundary layer developing on a horizontal cylinder imbedded in a porous medium is obtained [13DP] through solution of the boundary layer equations.

Experimental studies were concerned with heat and mass transfer in an unsaturated porous medium. A downward heat flux through a column of sand created three regions with vapor, liquid and vapor, and liquid filling the voids in each of the three respectively [24DP]. The temperature and pressure field in a porous plug with a pore size of 10 μm was measured [17DP] with vaporization occurring in the plug. A model [3DP] describing heat and mass transfer in unsaturated porous media was based on irreversible thermodynamics.

Experimental investigations contributed primarily to our knowledge in heat transfer in fluidized beds. A comparison of heat transfer data with flow visualization on a flat surface established [21DP] that heat transfer depends strongly on the inclination of the surface. Increasing pressure in a bed is beneficial [17DP] for the heat transfer to a immersed vertical wall. The following equation was found [15DP] to express heat transfer from a plane surface to a liquid–solid fluidized beds within $\pm 14\%$.

$$Nu = (0.0325\ Re + 1.19\ Re^{0.43})\,Pr^{0.37}(1-e)^{0.725}$$

Re, denoting the particle Reynolds number, is based on the terminal free fall velocity of the particle in the liquid, *e* is the bed voidage. A cavity is initially formed under a body immersed in an air-fluidized bed [9DP]. It rearranges the bed and increases heat transfer. Experimental results on heat transfer from single horizontal finned tubes in an air-fluidized bed of uniform particles [16DP] were compared with results on bare tubes. The fins improved heat transfer. Heat transfer on horizontal staggered smooth tube and fin-tube bundles was studied [18DP] in a fluidized bed of burning coal particles and in model beds. Heat transfer to vertical tube bundles in fluidized beds of particles with 0.8 to 3.1 mm dia. increased [8DP] with increasing pressure. Similar experiments [6DP] were concerned with heat transfer to the walls of the bed. Heat transfer in a three-phase fluidized bed was shown [11DP] to increase at the same rate as the decrease in the liquid holdup. A model was presented [12DP] to calculate heat transfer from immersed surfaces to large particle fluidized beds (1 mm or more). Conduction and convection at the interface is considered.

NATURAL CONVECTION—INTERNAL FLOWS

Interest in natural convection in enclosures remains high, as indicated by the large number of recent papers. As usual, there is considerable interest in convection in horizontal layers heated from below, and in differentially heated vertical and inclined layers. Subjects of growing interest include double diffusive convection where concentration gradients as well as temperature gradients provide buoyancy forces, flow in porous media with applications to geothermal heat recovery, convection in fires, and thermocapillary flows where surface tension plays an important role in driving the flow.

There is continued interest in convection in horizontal layers heated from below including analysis of the planform at low Rayleigh number and effects of side walls, variable properties, and potential internal energy sources. An analysis of convection in a high Prandtl number fluid shows conditions for bimodal and square patterns of convection and the impact of the flow on the Nusselt number [17F]. A one-equation model of turbulence has been applied to predict the Nusselt number at high Rayleigh number [26F]. The influence of variable fluid properties and boundary conditions on thermal convection has been demonstrated [10F]. Measurement of heat transfer across a horizontal layer of a fluid with highly temperature dependent viscosity can be predicted from the results for a constant viscosity fluid using a viscosity in the Rayleigh number determined at the average temperature of the boundaries [51F]. A convenient relation for the density variation of water has been used in calculating the onset of flow in a horizontal layer when the temperature is near the density extremum of water [35F]. The Galerkin method has been used to predict heat transfer in a vertical channel heated from below and having either perfectly conducting or perfectly adiabatic walls [16F]. The influence of side walls on stability was analyzed in another study [67F]. The onset of flow in a horizontal layer with variable temperature difference on the horizontal surfaces indicates either transverse or longitudinal roles, depending on the temperature difference [68F]. Observations of the convection pattern in nematic liquid crystals heated from below show the influence of stabilizing and destabilizing magnetic fields [54F]. Measurements of the time scale for transition in a layer of fluid with a step change in internal energy sources are used to check a boundary layer model for heat transport from the layer [27F]. Empirical relations for the heat transfer in a horizontal layer heated from below have been used to predict rollover of layers of different density in an LNG storage tank [23F].

A numerical solution for the multicellular convection in a vertical slot shows the influence of aspect ratio on heat transfer across such a differentially heated layer [30F]. Velocity measurements near the heated vertical wall in a rectangular enclosure indicate 2-D flow in the central region of the enclosure [40F]. The corner flows in a differentially heated cavity at high Rayleigh number and high Prandtl number exhibit a double structure with the outer layer dominated by convection [5F]. Secondary flows due to stratification in a differentially heated vertical layer have been observed [55F]. Analysis of the effect of nonlinear density stratification in a vertical layer of water shows the onset of a travelling wave [57F]. A partially divided differentially heated layer has been examined experimentally and numerically for low Rayleigh number flows [31F].

Measurements with inclined fluid layers indicate that the average heat transfer across a layer is closely represented by the heat transfer in the central section at sufficiently large aspect ratios and angles of inclination less than 60° from the horizontal [12F]. Finite difference calculations for the 3-D flow in an inclined layer have been performed for low Rayleigh number flow [39F]. Convection in an inclined rectangular box with partially heated opposing walls has been studied [9F]. Laminar flow in a tilted square cavity has been calculated for several angles of inclination [48F].

Flow visualization and heat transfer measurements have been obtained over a range of Rayleigh number and Prandtl number for convection across a channel with a cross section in the form of a parallelogram [56F]. The Nusselt number for convection across a triangular enclosure is found to vary as the Rayleigh number raised to the 0.59 power [44F]. A related analysis of convection in a triangular enclosure with a hot bottom wall shows that the flow is generally in the form of a single elongated cell [43F]. Heat transfer across a differentially heated cavity with a central vertical partition blocking part of the flow is very sensitive to the conductance of the partition [36F].

A number of studies considered the convection in the annular region between one body and the surrounding enclosure. A radial transformation was used to map the boundaries and aid in predicting the laminar convective flow in the annulus between two eccentric cylinders [47F]. A general relationship was developed to correlate early experimental results for laminar convection in horizontal annuli [6F]. Density inversion in water has a significant effect on the general flow pattern within a differentially heated horizontal annulus [66F]. In a vertical annulus, measurements of combined radiation and natural convection have been performed [28F] with either air or helium as the convecting fluid. Experiments using air to study convection in the annulus between vertical cylinders of different height indicate that the average Nusselt number is nearly independent of the eccentricity and the vertical position of the inner cylinder [61F]. Measurements of convection between a cube and a surrounding sphere are used to develop a general equation for heat transfer between a body of more or less arbitrary shape and a surrounding sphere [46F]. Finite element methods are used [8F] to determine the flow and heat transfer in the region between a square cylinder and a surrounding circular cylinder at low Rayleigh numbers. Calculations of the convection around a heated copper block immersed in a tank of water have been used to simulate the flow in a reactor core catcher [14F].

In double diffusive convection, buoyancy differences are due to two gradients, usually one being temperature, the other being concentration of one species in another. Experiments in double diffusive convection are compared to an analysis of flow and heat, momentum and mass transfer [32F]. Thermal diffusion effects on stability and formation of salt fingers in double diffusive convection have been analyzed [33F]. A linear stability analysis has been performed for a vertically stratified fluid in which mixed concentration and temperature gradients in the horizontal direction combine to provide a constant density in a given horizontal plane [24F]. Experiments in liquid mixtures of ^3He–^4He heated from below show effects akin to double diffusive convection [29F].

Buoyancy-driven convection in porous media occurs in insulation, in geothermal wells and in other systems. The analysis of convection in a porous medium bounded by two horizontal walls with linear temperature variations along the walls has been performed [42F]. A preferred mode of flow has been determined by stability analysis for finite amplitude convection in a porous layer with finite conducting boundaries [50F]. Both linear and nonlinear stability theory have been applied to determine the onset of flow in a differentially heated vertical porous layer [52F]. Numerical calculations for a differentially heated cavity of porous material with one of the sidewalls permeable, show reverse flow near this wall [22F].

Counterflow is found across the boundary between a vertical porous layer and the surrounding fluid [4F]. An analysis of transient convection in a fluid-saturated, porous medium contained between two concentric cylinders shows the time required for transient effects to die out [15F]. Experiments on convection in a porous medium filling the annulus between two vertical cylinders have been performed to simulate the heat loss from nuclear waste storage containers [49F]. Scaling arguments and numerical analyses are used to predict transient natural convection in a triangular shaped cavity filled with porous material [45F]. A developed code for predicting flow and heat transfer in porous media has been used to predict the heat loss from spent fuel elements in a storage pool [20F].

Buoyancy driven plumes are of interest because of their occurrence in the atmosphere, oceans, fires, and many engineering phenomena. The volume flow of a buoyant plume has been measured from the position of the interface formed with the entrained flow [1F]. An approximate solution for a laminar plume is valid for flow in a weak magnetic field [21F].

Experiments on the flow above a heated source located in a fluid layer stratified by a salinity gradient, show a hierarchy of plumes with a number of vortices [65F]. A special inlet manifold has been designed for introducing a buoyant jet into a liquid storage tank without changing the initial stratification [19F]. The importance of heat transfer and buoyancy processes in analyzing a fire in a large building have been demonstrated [13F]. The rate of growth of a developing fire in a compartment has been calculated [58F] using experimentally determined data for heat and smoke generation. An analysis shows the influence of buoyancy effects on turbulence characteristics [53F].

Thermosyphons are fluid loops in which the circulation is due to the difference in the buoyancy force in the upward and downward flowing legs. In some systems a forced convection is also imposed on the flow, and in others, boiling or the presence of vapor bubbles has a strong influence on the difference in pressure-head of the two legs of the loop. The influence of asymmetric heating on laminar mixed (forced and natural) convection in a thermosyphon has been studied both for aiding and opposing flows [41F]. Viscous dissipation and pressure work are shown to be of comparable magnitude in a free convection loop and should be considered together in an analysis of thermosyphons [3F]. Visualization of the flow in an inclined two-phase thermosyphon is used to identify key heat transfer mechanisms [37F]. The effects of geometry and working fluid on critical heat flux in a closed two-phase thermosyphon have been determined [25F]. The instability in a thermosyphon with boiling fluid is not greatly reduced by throttling the flow [64F].

Surface tension driven (thermocapillary) flows occur when a heated liquid layer has a free surface. The flow of a liquid in a one-quarter plane bounded on the upper surface by a passive gas and on one side by a semivertical wall shows the importance of capillary effects following a step-change of temperature on the vertical wall [11F]. Analyses of a layer with a free surface heated from below show the instabilities present with a horizontal temperature variation along the lower bounding surface [59F, 60F]. The influence of aspect ratio on the thermocapillary driven flow field in a differentially heated channel has been demonstrated [63F]. The stability of convection with a localized heat source on a free surface was examined [7F]. Linear stability analysis has been used to predict the flow with concentration and temperature-dependent surface tension for a horizontal layer [34F].

In mixed or combined convection, the flow is due to both buoyancy and externally driven or forced flow. An analytical solution for mixed convection in the entry region of a heated vertical channel indicates the presence of moving periodic cells when natural convection dominates [70F]. The heat transfer from a heated cylinder attached to a vertical plate is increased when the plate serves as a wall of a surrounding vertical duct [62F]. With mixed convection in an open horizontal channel the different flow regimes are delineated by values of the Grashof number divided by Reynolds number to the 3/2 power [69F]. Perturbation and finite difference methods indicate that both Prandtl number and Rayleigh number have a profound effect on the flow pattern for mixed convection in the region between horizontal concentric cylinders [38F]. The flow in thermal energy storage tanks is strongly dependent on the Froude number of the inlet flow [2F]. An analysis indicates the convective pattern around melting cladding after loss of sodium coolant in a fast reactor excursion [18F].

NATURAL CONVECTION—EXTERNAL FLOWS

The results of approx. 45 investigations of the natural convection heat transfer from flat plates in an infinite medium were reviewed and mean empirical relations were determined for the vertical- and horizontal-plate cases [26FF]. New correlations are presented for natural convective heat transfer from vertical isothermal surfaces in gases and the influences of variable properties are accounted for by using empirical equations that are of the form $Nu = g(Ra)\cdot f(Ra,\ Tw/T_\infty)$ [10FF]. For large Pr a simple relation for the propagation of the effect of the leading edge up a vertical plate generally agrees with results of past studies [6FF]. Space–time correlations of velocity and temperature fluctuations in the boundary layer of a vertical isothermal plate in air or N_2O at various pressurees provide estimates of turbulent scale [27FF]. The problem of how a free convection boundary layer on a vertical surface negotiates a small hump or indentation on the surface is discussed [29FF]. A transformation method is applied to study natural convection along irregular vertical surfaces and a sinusoidal surface is used as a specific example to demonstrate the advantages of the transformation method [44FF]. A numerical and experimental study of flow along an unheated plate above an isothermal plate demonstrates that the results are strongly influenced by the plate-fluid thermal conductivity ratio [24FF]. A new correlation is presented for natural convection heat transfer from a vertical isothermal surface in cold water and the correlation contains only one additional parameter beyond the Nusselt, Grashof and Prandtl numbers [5FF]. Calculations of the heat transfer from a flat plate in water include the effects of a melting ice surface and the density extremum [31FF]. The flow adjacent to a vertical isothermal surface immersed in saline water has been studied using a new density relation [19FF]. The linear stability of a steady plane parallel convective flow of a binary mixture in a plane vertical layer is considered with allowance for the thermal diffusion effect [15FF]. A numerical solution for the free-convection flow past a vertical semi-infinite flat plate embedded in a highly saturated porous medium has been developed by allowing the plate to have a nonuniform heat flux distribution [30FF].

A technical note describes an investigation of some aspects of the free convection in a corner whose walls consist of an isothermal vertical flat plate of finite height and an infinite adiabatic horizontal surface [35FF]. Unsteady free convective boundary layer flow over a semi-infinite horizontal plate is analyzed employing the method of matched asymptotic expansions for the case when the plate temperature oscillates with a nonzero mean and the free stream is at rest [42FF]. Laminar natural convection from a horizontal plate and the influence of plate-edge extensions were studied by a finite difference analysis and by experiments [16FF]. An analysis is performed to study the heat/mass transfer and vortex instability characteristics of buoyancy induced flows that result from simultaneous diffusion of heat and mass in laminar boundary layers adjacent to horizontal and inclined surfaces [9FF]. The breakup of a thin liquid layer heated from below has been studied [18FF].

Eight previously published correlation equations plus one new correlation for heat transfer by natural convection from horizontal isothermal cylinders are tested against a fairly extensive body of experimental data called from the literature for $10^{-8} < Ra < 10^{8}$ and $0.7 < Pr < 4 \times 10^{4}$ [13FF]. In a transient numerical analysis, the time histories of the isotherms and streamlines in the natural convection flow field around a horizontal cylinder were computed beginning with a step change in the cylinder temperature and ending when steady state was reached [36FF]. For natural convection of a coal oil mixture around a horizontal cylinder it was found that when the bulk temperature of the mixture was high the experimental heat transfer data was in good agreement with a similarity solution of the natural convection equations in a power-law fluid [2FF]. Two series of experiments were performed in order to measure the average and the local heat transfer coefficients in laminar natural convection around horizontal circular cylinders whose surface was in part isothermal and in part adiabatic [12FF]. An investigation was performed of the effects of vibration on the natural convection from horizontal cylinders [22FF]. Similarity velocity and temperature profiles, as well as heat transfer results, are presented for laminar natural convection from slender needles with axial power-law wall heat flux variation [7FF].

Empirical formulas are proposed from experiments on free convective heat transfer from a cylinder array arranged in a vertical line and subsequent experiments were used to examine the effect of using two parallel plates to enclose the array [40FF]. Experiments were carried out to determine the effects of transverse misalignment on the natural convection heat transfer characteristics of a pair of equi-temperature, parallel horizontal cylinders situated one above the other [38FF]. Both laminar and turbulent heat transfer from single and double rows of closely spaced isothermal heated cylinders were investigated numerically [14FF].

Theoretically, it is argued that the transition to turbulence in a buoyant plume occurs when the time of viscous penetration normal to the plume becomes comparable with the minimum time period with which the plume can fluctuate as an unstable inviscid stream [23FF]. A 2-D numerical model for predicting the steady surface thermal plume in the near field has been presented [11FF]. A steady state solution is obtained for the linear system of Navier–Stokes equations in the Boussinesq approximation for free axisymmetric convection flows from a point heat source in a stably stratified fluid [21FF]. An experimental study was conducted of plane plumes in water which is at or near the extremum temperature [20FF]. When a salinity gradient is heated at a single point, three kinds of layers are observed: the first kind is formed above the basic plume from a hierarchy of secondary plumes on top the basic one, the second develops around the upper part of the basic plume and the third forms around the lower part of the basic plume [41FF]. The thermal instability for 2-D stagnation flow for Prandtl numbers ranging from 0.7 to infinity was studied using an analysis that represents an exact solution since neither the boundary-layer approximation nor the parallel-flow assumption was invoked [8FF].

Both analytical and numerical techniques were employed to solve for the velocity and temperature fields in a 2-D mixed convection plume for the Prandtl number range from 0.72 to infinity [17FF]. The buoyancy effects on the thermal boundary layer induced by a horizontal forced flow along an infinite vertical cylinder with a step change of surface temperature is studied by a finite-difference method [43FF]. A theoretical study was performed of the laminar mixed convection from a horizontal cylinder in a cross stream [3FF]. Laboratory model data are presented for the 3-D time averaged thermal characteristics of a buoyant rectangular surface thermal plume in a crossflow [25FF]. A boundary-layer analysis of mixed convection about a point heat source is made in terms of the parameter Gr/Re^2 for the cases when the buoyancy effects are favorable or adverse with respect to the imposed vertical stream [34FF]. The mixed convection in an axisymmetric point heat source due to a vertical free stream is analyzed using the boundary layer equations for the cases of favorable and adverse buoyancy effects [1FF]. Two aspects of the influence of double diffusion on convection from point buoyancy sources were addressed; double-diffusive convection acting in conjunction with buoyancy from an isolated source in an unconfined environment and the problem of when fluxes of properties occur in the opposite direction to that of the initial buoyancy [28FF].

The authors of [37FF] state that their experimental evidence stands in opposition to the use of King's rule for evaluating the characteristic length for multidimensional natural convection problems. Unsteady 2-D free-convective flow through a porous medium bounded by an infinite vertical plate is considered when the temperature of the plate is oscillating with time about a constant nonzero mean value [33FF]. A numerical study was made of the free convection flow over isothermal and nonisothermal rotating flat plates subject to a linear variation of the gravity field; both the cases of hot and cold plates were considered [32FF]. The onset of convection in a cylindrical volume of fluid bounded above and below by rigid, perfectly conducting surfaces and laterally by a wall of arbitrary thermal conductivity was examined [4FF].

CONVECTION FROM ROTATING SURFACES

Heat transfer has been studied for the configuration in which there is a radially outward flow between two coaxial stationary or corotating disks [9G]. Laminar convection has been investigated for non-Newtonian power-law fluids in contact with rotating disks [11G]. Reference [5G] considers the effect of Prandtl number on heat transfer from an isothermal rotating disk with blowing at the wall. For a bounded cylindrical layer of fluid heated from below, the effect of rotation on stability has been determined [1G]. Experimental results have been presented for a rotating fluid heated from below [10G]. Reference [3G] deals with forced convection from a disk rotating in a vertical plane. Numerical solutions are given for the thermal instability of a rotating micropolar fluid layer [8G]. The thermal instability is also considered in [6G] for a horizontal fluid layer under rotation and internal heat generation. The stability of rotating cryogens is treated in [7G]. Reference [2G] reports experimental and theoretical results for convection in rotating spherical shells. A 3-D unsteady numerical simulation has been made for convection in rotating layers [4G].

COMBINED HEAT AND MASS TRANSFER

Studies involving combined transport of mass and heat are encountered in a number of applications. Some specific studies that we include in this category are film cooling and related processes in impingement heat transfer.

Measurements in a short duration wind tunnel indicate that the effect of the temperature difference between the gas and the surface is small when the wall temperature is less than the free-stream temperature [10H]. Numerical calculations along with experiments indicate the film cooling effect following injection through tangential multiple jets [6H]. The assumption of a Gaussian temperature profile and an entrainment function are used to study film cooling with 2-D tangential or normal injection [13H]. Mass transfer measurements indicate the film cooling effectiveness on suction and pressure sides of a turbine blade following injection through two rows of staggered film cooling holes [3H]. An analysis of a surface ablating with a time varying heat input shows strong influence of different approximations that are made to predict the ablation rate [1H].

An empirical relation has been developed for the heat transfer to a row of impinging circular jets with cross-flow [11H]. Heat transfer with an array of impinging jets within a duct flow has been determined experimentally [2H].

The heat and mass transfer occurring in the absorption of a gas or vapor into a laminar liquid film depend on the Peclet and Lewis numbers as well as on the equilibrium characteristics of the working media [4H]. Heat and mass transfer coefficients were measured and computed for steam absorption into a falling wavy film of liquid LiBr [12H]. Heat and mass transfer to a drop from a surrounding polyatomic gas has been analyzed [8H].

The overall balance for heat and mass transfer with parallel, counter and cross-flows in grain drying has been analyzed [9H]. A spouted bed heat and mass exchanger in which a jet of fluid enters a bed of tablets or other particular material has convenient drying characteristics [5H]. From another set of experiments on a spouted bed heat exchanger, optimization equations are developed for pressure drop and heat and mass transfer [7H].

BOILING

Nucleate boiling

The fundamentals of nucleate boiling are still under investigation. An analysis of the conditions of equilibrium for a vapor bubble [8J] showed support for earlier analytical conclusions and experimental evidence that a bubble can remain in a state of stable equilibrium in a finite system under certain circumstances. It was experimentally shown that a previously imposed pressure history had a strong deactivating effect on surface cavities serving as nucleation sites [19J]. In a high speed motion picture study, nucleation site density, bubble departure diameter, and frequency were determined for saturated atmospheric pressure water heated by a wire [48J]. Evaluation of the relative contributions to the boiling heat flux in those experiments suggested that the enhanced convection induced by bubble motion was never the dominant mode of heat transfer, but instead contributed less than natural convection at low heat fluxes and less than latent heat transport at high heat fluxes. In another study [38J], for which the goal was to predict interfacial transport terms to allow application of a two-fluid model, the nucleation site density was found to be of vital importance. A correlation for site density was developed and compared favorably with experimental data.

Shape and motion of bubbles are of concern. One investigation examined the effects of Marangoni convection [37J] on bubble motion while a few dealt with the bubble conditions at the time of separation from a surface. An equation was developed for the break-off radius of bubbles with attention to the vanishing of bubble and surface interactions at the instant of departure [44J]. Two unrelated studies considered the optical distortions imparted to our views and photographs of departing bubbles by the local temperature gradient at the heated surface [12J, 80J]. In an apparatus designed to minimize these distortions [13J], individually formed bubbles showed no evidence of retarding effects due to surface tension. Delay times of nucleation sites near a given site were shown [63J] to be related to the square of the separation distance for distances less than twice the bubble diameter. A model based on thermal diffusion through the heating solid fit the experimental data well. Laser interferometry was used [40J] to measure the thicknesses of microlayers during bubble growth in subcooled boiling of both water and ethanol. Analysis of the data implied that evaporation of the microlayer accounted for no more than one half of the rates of heat transfer measured.

The lower heat transfer rates associated with nucleate boiling of mixtures of substances were addressed in two different ways: a method for predicting heat transfer coefficients for boiling of binary mixtures was demonstrated using phase equilibrium data [65J], and another method was proposed [54J] using the liquid phase mass transfer coefficient.

Forced convection boiling

Experiments with both vertical and horizontal tube flows [5J] showed negligible differences in pressure drop between the regime of nucleate boiling and the regime of "forced convection boiling" with no vapor formation at the tube wall. The investigator concluded that the absence of a significant change in the wall shear stress implied an absence of effects of bubbles except as latent heat transport media. Theoretical models of heat transfer in these two regimes were constructed upon this conclusion. An experimental study [1J] determined that there was very little difference in heat transfer coefficients measured during nucleate boiling for upflow and for downflow in vertical systems despite obvious differences in void accumulation. Measured heat transfer coefficients are reported for flow boiling of refrigerant 114 in upflow and downflow in stainless steel tubes [17J]. Strong effects were observed of the influence of 180° bends as much as one meter upstream of the test section. A comparison of available data for subcooled boiling in annuli demonstrated the applicability of the Shah correlation (developed for flow in tubes) to boiling in cylindrical annuli heated by inner, outer, or both walls [56J]. An experimental investigation was carried out in an internally heated annular vertical flow of refrigerant 113 to study the statistical character of static pressure fluctuations and chordal-averaged vapor fractions [30J]. Results suggested that diagnosis of flow regimes should be possible based on measurements such as these.

Experiments were performed [49J] with analog feedback control to achieve a steady heater temperature during transition boiling. Results for nucleate boiling, transition, and film boiling were presented as Laplace transform transfer functions. Other investigators [78J], concluding that traditional experiments of transition boiling provide inadequate control of the heat generating element, performed three sets of experiments with one heating element by controlling either current, voltage, or temperature (resistance) to accumulate information on the true boiling curve. A simple homogeneous flow model was demonstrated to provide reasonable agreement with measured pressure drop oscillations and density wave oscillations in a single-channel boiling up-flow system [21J]. Experiments with five enhanced surface tubes and one bare tube explored the effects of these surfaces on two-phase flow instabilities in vertical boiling flows [43J]. Pressure drop vs flow rate characteristics were determined, from which the boundaries of instability to pressure drop and density wave instabilities were derived for each internal surface. An analytical model was presented [47J] for pressure drop in steady liquid/vapor countercurrent flow as a function of inlet vapor flow rate and applied heat flux. Experiments and analysis were reported [42J] concerning countercurrent stratified flow of condensing steam and water in a shallow rectangular channel. Models of slug formation from cocurrent horizontal flows predicted the onset of flooding of these systems for nearly horizontal flows. Measurements were made of film thickness and interfacial shear stress. It was determined that the condensation had little effect on the overall behavior. In a brief survey article of two-phase flow [26J] three current approaches to prediction of two-phase flows were described: empirical, analytical, and phenomenological, with the latter being suggested as the most promising avenue for further efforts.

Transient boiling heat transfer experiments were reported [35J] using an electrically heated platinum wire centered coaxially in an upward flow. Two patterns of change of wall superheat with heat flux were observed. In the more common pattern, wall superheat exceeded steady state values for intermediate heat fluxes, but coincided with steady values or the extrapolation of their curve at high heat fluxes. Maximum heat fluxes for these transients increased with decreasing transient period (increasing rate of change of flux) and with increasing pressure, velocity, and subcooling. In a temperature controlled transient boiling experiment with refrigerant 113 [74J], measured values of critical heat flux, CHF, were shown to be dependent upon the rate of change of the surface temperature of a thick heating element. Differences from steady conditions of critical heat flux were demonstrated to correlate well with the rate of change of the interface temperature. It was suggested that analysis of heat transfer in two coupled media can in general be decoupled using this rate of change. The CHF for quenching processes was shown to depend upon the direction of the motion of the quench front, the quenching being a complicated conjugate transient problem. In another investigation of transient conditions [55J] a model was formulated for the maximum heat flux based on the balance between liquid layer replenishment and evaporation.

A model was developed for predicting CHF in high velocity flow of low quality two-phase mixtures in heated tubes [70J]. In this model the breakdown of turbulent exchange between the bubbly layer and the core is considered to be the limiting phenomenon. Another model was presented as applicable to both pool boiling and forced convection CHF for saturated boiling at submerged bodies [24J]. In this latter model it was held that a stable liquid film of definite thickness during boiling is evaporated at CHF due to restrictions of liquid feed to the surface; predictions compared favorably with data for pool and flow boiling in several geometries. Dealing with the particular geometry of a horizontal tube with upward cross-flow [36J], CHF was modelled in two flow regimes: low velocity with bubble-like departure of vapor, and high velocity flow with sheet-like departure of vapor. Good agreement with limited existing data was reported. Steady film boiling in this same geometry was modelled using a boundary layer approach for the two-phase flow [58J]. The model tended to underestimate measured heat transfer coefficients. It was concluded [29J] on the basis of a consistent interpretation of previously reported experiments of liquid metal fast breeder reactor (LMFBR) natural convection cooling that a typical reactor subassembly can be safely cooled without dryout at decay heat power levels which are less than 8–10% of nominal average power.

An investigation of rewet heat transfer in vertical flow of refrigerant 113 was carried out using copper test sections of high thermal capacity [68J]. Maximum heat fluxes coincided well with measured critical heat fluxes, and wall superheats at the rewet condition were found to vary greatly with the flow quality. Experiments with rewetting of horizontal annular channels [50J] demonstrated that stratification effects are significant and stronger at low flow rates. Rewetting velocity was found to increase with increasing flow rate and with reduced initial surface temperature. Rewetting by a falling liquid film was investigated with refrigerant 113 flowing down the outside of a stainless steel tube [67J]. Spatial and temporal variations of temperature were measured with sufficient accuracy to derive the boiling curve from these experiments. The boiling curve and the rewet front velocity were little affected by the film flow rate; the boiling curve was likewise little influenced by initial wall temperature or wall thickness. Maximum heat fluxes observed were about twice the critical heat flux predicted for pool boiling. Experimentally determined post-dryout heat transfer coefficients inside a steam generator tube heated non-uniformly by the countercurrent flow of sodium were correlated with the more abundant data from experiments with uniform electric heating [69J].

In an investigation of two-phase blowdown of a vessel initially containing saturated liquid [27J, 28J] experiments showed that transient critical two-phase flow is similar to steady critical two-phase flow and that an initial depressurization was followed by a period of nearly constant pressure as the rate of vapor formation approximately balanced the volumetric discharge rate. Three models, to be used in series, were developed to describe the blowdown sequence: a single phase blowdown, then a period of pressure recovery with thermally governed vapor bubble growth, followed by attainment of thermodynamic equilibrium of liquid and vapor within the vessel. The model showed considerable sensitivity to the number of potential nucleation sites within the vessel and thus a sensitivity to the surface area of internals.

An iterative numerical technique was presented for determining distributions of two-phase flow amongst multiple paths between manifolds, accommodating homogeneous flow with and without heat transfer [15J]. Attention was paid to disturbance waves in thin liquid film annular flow in a vertical tube [64J]. A model was developed for heat transfer and pressure drop in these circumstances, capable of predicting heat transfer coefficients well but tending to overpredict film thickness. Wave amplitude and time rate of passage are input parameters in the model and were measured in accompanying experiments.

The effects of wire gauze-covered internal walls of horizontal steam generator tubes upon critical heat flux were explored [62J]. For large mass fluxes higher heat fluxes or higher flowing qualities at CHF were obtained. At lower mass fluxes, however, CHF occurred at lower heat fluxes or lower qualities. Two-phase pressure drop in the gauze-surfaced tube was correlated using a homogeneous flow model. The Martinelli–Nelson correlation was found to under-predict pressure drop data obtained for mixtures of refrigerants 12 and 13 in experiments in horizontal tubes [59J]. Fouling of argon-evaporating surfaces with carbon dioxide present in very small quantities in the argon was reported and explained by means of bubble growth mechanisms [45J].

Natural convection boiling

Effects of pool geometry and of spacing between heated tubes upon pool boiling characteristics were examined experimentally [22J] using identical finned heated tubes immersed horizontally in a small cylindrical and a large rectangular vessel containing refrigerant 11. Differences were substantial at moderate heat fluxes but vanished at larger heat fluxes. Experiments with various combinations of heated and unheated horizontal tubes in a bundle and a solitary heated finned tube were conducted in pool boiling of refrigerant 11 at 1 bar [23J]. It was tentatively shown that a simple vertical tube pair arrangement provides heat transfer coefficients representative of tubes in bundles of greater number. Influence of bundle spacing as well as effects of pressure were observed with bubble characteristics and heat transfer coefficients in a small boiling heat exchanger [60J].

A model was proposed for nucleate boiling at high heat flux, heat fluxes between the critical heat flux and 60% of the critical heat flux [4J]. The chief mechanism was hypothesized to be conduction through a macrolayer of liquid, as nucleate boiling was suggested to be suppressed under high heat flux conditions. A theoretical expression was proposed for the thickness of such a macrolayer and a mechanism for layer formation was described [3J].

Instabilities on heated wires were described [33J] and observations of the motion of the wave of transition from nucleate boiling to film boiling on inclined wires were reported [79J]. Temperature fluctuations and vapor formation at small heated surfaces flush with an unheated wall were experimentally observed [57J]. Those experiments showed no evidence of burnout despite heat fluxes of up to 12×10^6 W m^{-2}.

Experiments with boiling of water, acetone, and refrigerant 113 in narrow annular gaps displayed three boiling regimes [73J]. The Bond number, a ratio of gap size to bubble departure diameter, appeared to be a determinant for nucleation under slightly deformed bubbles, which occurred for Bond numbers slightly greater than unity. Experiments were performed in narrow eccentric annular gaps simulating the crevice between a heated tube and a support plate [31J, 32J]. The variations of eccentricities were found to have small effects relative to tube/support plate contact; separations of the order of 0.05 mm or less resulted in some transient dryout behavior. Large rates of vapor formation at a line of contact produced a heat transfer enhancing sweep of vapor at roughly 60° from the contact line. A correlation was developed for critical heat flux in narrow vertical annuli with closed bottoms [10J]. Based on countercurrent flooding conditions, the correlation is independent of liquid surface tension. Boiling of dielectrics in slots of 0.5 to 4 mm height displayed considerably different (enhanced) behavior from pool boiling on a plane surface [7J]. Boiling crisis in a thermosyphon was judged to be of hydrodynamic nature associated with the vapor phase achieving a critical velocity by which the liquid film is detached from the surface [2J].

Experiments with surfactants in water under saturated atmospheric boiling conditions showed improvements in both the heat transfer coefficient and the critical heat flux with increased concentration of the surfactants [72J]. Pool boiling experiments with three drag-reducing polymers in water produced enhanced boiling characteristics with two of the polymers but degraded heat transfer with the third [53J]. The investigators concluded that the changes had nothing to do with the drag-reducing effects of the additives. An empirical equation was developed for predicting heat transfer coefficients in a concentrator with natural convection flow through external boiling tubes [34J].

Other boiling and evaporation studies

Natural convection and surface tension effects were visualized in small evaporating droplets on an inclined surface with a temperature gradient through use of the motion of suspended solids and also by use of laser shadowgraphy [76J]. Bénard cells were observed in a ring of intermediate radius for droplets of some fluids evaporating on a mildly heated surface [77J]. Experimentally determined single droplet evaporation rates in high temperature air showed that higher temperatures, resulting in higher evaporation rates, resulted in lower Nusselt numbers [51J]. Numerical treatment of evaporation of single droplets in the Reynolds number range 10–100 agreed well with experimental data [52J]. Mass transfer reduced the friction drag but increased the pressure drag, with a net result of agreement with the standard drag curve if free stream density and a particular representative viscosity are used.

Local mass transfer coefficients (and by inference, heat transfer coefficients) were determined experimentally in the vicinity of a scraping blade in a thin film evaporator [71J]. An analytical model was shown to agree within a few percent with a finite difference approach for predicting film vaporization of hydrocarbons in a stream of hot air [16J]. Experiments conducted with a circular disk heating surface in natural convection with varying heights of saturated liquid above the surface [66J] suggested that at very small film thicknesses the heat transfer is solely by conduction. For greater thicknesses, the heat transfer coefficients appeared to be quite comparable with those for saturated pool boiling. A correlation was developed from experimental results of natural convection evaporation from a shallow unheated pan of water to atmospheric air [61J]. The Sherwood number varied with the Rayleigh number to the exponent 0.205, and the effects of pan sidewall height and of the extent of a horizontal frame at the sidewall height were measured, correlated, and found to induce no change in the Rayleigh number dependence. A numerical investigation of evaporation from a stationary body of water to a laminar stream of air, superheated steam, or a mixture of air and steam [11J] showed that at low temperature the evaporation rate decreased with increased humidity while above an inversion temperature of about 250°C the evaporation rate increased with humidity.

Consideration of the length and velocity scales of eddies formed in a steam vent led to an explanation of the onset of a roughened vapor/liquid interface during the collapse of the discharged steam and produced a theoretical estimate of the interface heat transfer coefficient [41J], the application of this work being modelling of BWR suppression pools. A 1-D experiment for the boiling and spreading of cryogenic liquids on water corroborated a model when reasonable, constant boiling rates were assumed in the model [9J]. Destabilization of film boiling by shock waves, investigated as a trigger for vapor explosions, was modelled in two ways, with and without assuming thermodynamic equilibrium between the phases [14J]. Both models displayed the same trends of observed data, and equilibrium appeared to be maintained if the shock rise time was longer than 100 μs.

A theoretical analysis of evaporation and condensation at the surface of a cylindrical body of liquid in its own vapor employed finite radial vapor velocities and demonstrated the need for a nonlinear analysis [46J]. Inadequacies of linearized theory were also demonstrated for half-space problems, as condensation and evaporation are not antisymmetric except for conditions at one particular value of a property parameter [75J]. A 1-D theoretical model was presented of evaporation and expansion of vapors from a metal surface with a high energy density source [25J]. The surface temperature was linked with the evaporation rate and hydrodynamic parameters.

The overall time-averaged heat transfer coefficient for a drop in an alternating electric field was shown to be governed by the Peclet number and a parameter defined as the thermal vibration number which related the frequency of the alternating field with the thermal relaxation time of the drop [20J]. At low Peclet number the alternating field enhances heat transfer, especially at low frequency, while at high Peclet number the field may enhance or detract from the time-averaged rate of heat transfer. The current state of understanding of the effects of electric fields on vaporization and condensation was assessed [6J], and areas are suggested for further exploration and future exploitation.

Centripetal acceleration and the corresponding hydrodynamic pressure gradient were charged with causing a decreased rate of desorption in boiling [39J]. Use of hydrophobic materials was demonstrated to counteract the depression of the desorption rate. A brief description was made of the variations in generation and transmission of acoustic emissions associated with different modes of boiling [18J].

CONDENSATION

Film condensation

Measured heat transfer coefficients and pressure drop data were presented for condensation of steam in tubes and annuli using several fin configurations. Fin efficiencies were presented [7JJ]. Numerical results for condensing on rectangular and triangular fins were compared and optimum fin dimensions were given in terms of the Biot number [13JJ]. Analytical comparisons of corrugated and tightly-ribbed tubes were presented. Slender and sharp surface profiles were shown to be superior to wide and round contours [1JJ]. A numerical method was presented for analysis of condenser tube heat transfer including condensation on porous, anisotropic surfaces. Complicated tube and baffle geometry was also incorporated [8JJ]. A comparison of the Chilton–Colburn and Von Karman analogies for condensation inside vertical tubes was presented. The analogies agreed with one another over the range of conditions analyzed [14JJ].

Reflux and natural circulation condensation in vertical inverted U-tube steam generators was experimentally investigated; various flow regimes were identified [2JJ]. Local heat transfer coefficients and condensation rates were measured in countercurrent, stratified flow of steam and subcooled water. Correlations were given for Nusselt numbers under smooth and wavy interface conditions. Basing the correlations on interfacial, rather than bulk, parameters was recommended [5JJ]. The effect of waves on vapor-side heat transfer was measured in the vertical tube film condensation process. The liquid Reynolds number was varied as a single vapor condensed from a noncondensable gas; no Reynolds number effect was observed over the Reynolds number range in the experiment [3JJ]. The effect of film waviness on condensation was experimentally investigated. Accurate simulation of large vertical condensers with laboratory setups was shown to be possible [9JJ].

An experimental study of condensation on cold walls during freeze-drying was made and the idea of regeneration of the surface by rapid heating was tested [4JJ].

Free condensation

The transition from dropwise to film condensation was experimentally investigated for ethanediol; transition mechanisms were proposed [11JJ]. The equilibrium shape and departure size of condensation drops on vertical surfaces were measured. The configuration of minimum total energy was used to develop a model which compared well with the measurements for acceleration fields up to 100 G [6JJ].

A theoretical analysis was presented for binary nucleation and subsequent heterogeneous droplet growth. Results were checked against water–ethanol data [10JJ]. Condensation rates were measured for dropwise condensation of steam. The heat transfer coefficient remained constant with an increase in surface subcooling to 10 K, then decreased. Maximum heat transfer rates of 10 MW m^{-2} were achieved [12JJ].

FREEZING AND MELTING

Theoretical and experimental studies of freezing or melting in cavities, on external surfaces or in porous media have been performed. Applications include continuous casting, reactor safety, latent thermal storage and thawing of frozen porous materials.

Analytical solutions to the Stefan problem continue to appear including a delineation of four possible cases depending upon the initial conditions [34JM]. A heat balance integral method was applied to the melting of a semi-infinite slab with prescribed surface heat flux and no subcooling [10JM]. A justification for the use of an enthalpy model in multidimensional phase change problems was given [37JM] in addition to a numerical solution technique. Interfacial wetting transition was examined in a 2-D melting problem using the three-state chiral clock model [17JM].

A pair of papers described the discrepancies between current models and experimental data for thermophysical properties of sodium near melting [1, 21JM]. An improved model was developed using a perturbation approach.

The 2-D continuous casting problem was transformed into a Cauchy boundary value problem which directly yields the solidification interface shape [27JM]. It was also shown that almost immediate solidification can occur at low velocities in continuous casting so that no free boundary exists [7JM]. An analysis of zone melting with multiple zones was presented [4JM] that indicated that the yield increases with the number of melting cycles.

Cavity problems can provide interesting results if the density changes and the volume is fixed. An analysis of water freezing inside a closed pipe indicated that as the water freezes, the pressure increases which lowers the freezing temperature [30JM]. Eventually the system can reach an equilibrium state without the liquid completely freezing in a constant temperature environment. The freezing of a liquid inside a sphere was analyzed without using boundary layer simplifications [13JM]. A numerical solution to the melting of a solid contained inside a horizontal tube was obtained [24JM] which included turbulent natural convection flow in the experimental phase. Experimental data was shown for comparison.

The shape of a vertical solid that melts when exposed to condensing vapor changes during the initial transient phase [32JM]. Eventually the shape becomes time invariant and is roughly a profile that shows the variation in local heat flux. Freezing around a cylinder was solved with an implicit numerical method that isolated the nonlinearity of the interface [22JM]. A computer model has been developed to predict ice growth on insulated cryogenic liquid storage tanks [16JM].

A 1-D exact solution for freezing of an infinite moist porous solid around a line heat sink was developed [3JM]. Approximate solutions were given for 2-D freezing of soil near a horizontal buried pipe [19JM]. Numerical studies were made on the thawing of moist spheres simulating coal particles [23] and cylinders simulating logs [29JM].

Exact solutions were developed for the Stefan problem with contact resistance at the interface [33JM]. The solution is valid for arbitrary initial and boundary conditions. The effect of radiation on melting was considered which included a two-phase region [6JM]. Exact and approximate solutions were given for specific cases. The radiative melting of snow was analyzed with experimental data obtained for comparison [31JM]. An analysis of freezing a mushy-zone was made which can be applied to the rapid solidification of an alloy [14JM]. The drag on a hot sphere with internal heat generation melting its way through a solid was obtained using a simple analysis [8JM].

A number of experimental papers appeared that concern freezing or melting. Flow visualization of a double diffusion ice–salt water problem indicated that natural convection flow could occur in either or both vertical directions depending on the given parameters [26JM]. A pair of papers described flow visualization experiments during melting or freezing in a rectangular cavity [11, 12JM]. The freezing process of paraffin in a sealed vertical tube was documented [23JM] as was freezing and melting in vertical tubes of circular or square cross section [20JM]. Freezing rates were found to agree with a simple quasi-steady conduction model but natural convection dominated the paraffin melting process. Measurements and analysis were used to study freezing of three different liquids within a horizontal tube [36JM]. The freezing front was symmetric about the tube centerline in agreement with the results for the vertical tube configuration with paraffin. The freezing of a liquid-filled open rectangular cavity was also studied [15JM]. The cooling rate of water with supercooling determined the appearance of dendrites and the phase front movement [25JM] in contrast to the work on paraffin that did not show these effects. Two papers considered the problem of frost growth and the variation of its effective thermophysical properties with time [2JM, 35JM]. The melting of a solid under a hot liquid whose density is larger than the melt was studied by two independent groups [9JM, 5JM]. The melt rises through the liquid creating an unstable natural convective system. The solidification of solute from a binary aqueous salt solution was investigated [18JM]. The interface was smooth until dendrites formed during the final stages of freezing.

RADIATION

Radiative heat transfer continues to attract considerable attention as documented by the large number of publications during the past year.

A new integral function has been introduced for computing the spectral emissivity of an isothermal volume, containing either soot or gaseous species or both [11K]. The reflectivity and transmissivity of an isotropically scattering, plane-parallel slab with stepwise variation of the single scattering albedo within the medium are calculated for an isotropic radiation field [14K]. Radiant heat flux calculations in planar, absorbing, emitting, and isotropically scattering layers have been accurately reduced to calculations in nonscattering layers by scaling laws [24K]. Studies of the effect of a single scatter phase function distribution on radiative transfer in absorbing–scattering liquids are reported [6K]. A finite element solution of radiative heat transfer in a 2-D rectangular enclosure with gray participating media provides accurate temperature distributions in the medium and wall heat flux distributions, even for media with very small opacities where most of the approximation methods break down [34K]. Studies of 2-D radiation in absorbing–emitting media using the P–N approximation show that the P–3 approximation can be used to predict emission power distributions and heat transfer rates in 2-D media with opacities of unity or greater [33K].

Using a Monte Carlo method it is shown that the absorption, scatter and extinction efficiencies of a fly ash cloud have a primary dependence on the complex absorption index of the particles with a secondary dependence on temperature and particle size distribution [17K]. Experimental investigations of thermal radiation in soot-containing flames in a wavelength range from 0 to 23 μm indicate that internal absorption of thermal radiation in flames requires wavelength-dependent calculations if accurate modelling is desirable [15K]. A gas turbine combustor using heavy fuels is considered. Radiation, smoke and temperature measurements in an experimental combustor at various air pressure, inlet temperature, and air fuel ratios show a diminishing rate of increase of radiation with soot concentration and reduced sensitivity of smoke to fuel hydrogen content at higher combustor pressure [30K]. Results of infrared measurements in the 8–14 μm spectral region of two coal-fired power plant plumes and area haze in the Four Corners of New Mexico in Nov. 1980, show an increase with time of the haze bulk extinction coefficient during a persistent anticyclonic synoptic situation [44K]. Absorption and extinction measurements in smoke produced by atmospheric combustion of diesel fuel at 10 μm indicate a mass absorption coefficient of 0.84 ± 0.076 m^2 g^{-1} and a total scattering coefficient of 0.15 ± 0.014 m^2 g^{-1}. Both values are normalized to the aerosol mass density [9K]. Radiative transfer through the atmosphere may be strongly affected by combustion-generated aerosols. A method for measuring the absorbing component is described [36K]. Temperature measurements in an automobile engine have been obtained by observing the CARS spectra of molecular nitrogen with an uncertainty of approximately 50–100°C [2K].

Using the modulation method of relative measurement of total emissivities, an instrument is described for determining the total emissivity of thin layers of various materials at temperatures between 223 and 423 K [13K]. An instrument for measuring spherical irradiance has a novel design feature consisting of a spherical, perforated receiving cavity [38K]. A portable instrument for measuring the emissivity of materials and coatings at room temperature is described in [35K]. The feasibility of absolute measurements of spatially inhomogeneous radiation is demonstrated and calculations show that the total errors in determining the local values of the density of radiant energy and of the incident radiant flux are 10.9 and 7%, respectively [3K]. A calorimetric method for measuring the emissivities and absorptivities of materials and fibers at temperatures between 170 and 370 K is described together with an error analysis [42K]. A generalized reflectance method for determining optical properties of absorbing materials overcomes the problem associated with nonideal surface conditions by applying transparent overcoats [29K]. The index of refraction in the near-millimeter wavelength range may be determined by using a mesh Fabry–Perot resonant cavity [40K]. A calculation method has been used to eliminate thermal radiation from effective thermal conductivities measured in a liquid within several layers of different thickness. The resulting "pure" thermal conductivities are independent of layer thickness which verifies the validity of the calculation method [8K].

Measured optical constants of fused silica and sapphire from 0.3 for 25 μm are in good agreement with data in the literature for the relatively small part of the spectral domain where they can be compared [23K]. Measurements of the temperature dependence of the refractive indices of fused silica and crystal quartz, in a wavelength range from 4500 for 16000 Å and from room temperature up to 4000°C, indicate that the average thermal coefficients of the refractive indices of those materials show opposite signs [48K]. Infrared optical constants collected from the literature can be reasonable fitted to the Drude model for noble metals and Al, Pb, and W [32K]. Studies of the infrared reflectivity and crystal structure of InS in the wave number range from 50 to 900 cm^{-1} confirm that the measured dispersion parameters have more explicit values than those previously reported for twin crystals [45K]. Measured infrared specular reflectances of pressed crystal powders and mixtures agree with averaged crystal-optic reflectances if the low density of powders of harder substances is taken into account [49K]. Infrared optical properties of solid monomethyl hydrazine, N_2O_4, and N_2H_4 are reported for cryogenic temperatures [37K]. Studies of the refractive index of bismuth germanium oxide ($Bi_{12}GeO_{20}$) in the range 1.2–5.0 μm at room temperature show that a Herzberger formula completely describes data of $n(\lambda)$, up to the visible region [10K].

Heating of thin films of tin disulphide above 410 K converts the amorphous structure into crystallized films which have reduced transmission at wavelengths longer than the absorption edge and the absorption edge shifts to lower wavelengths [16K]. The development of an efficient and durable medium band antireflection coating on germanium for the 8.0–11.5 μm wavelength region is described [25K]. A new technique for determining the i.r. optical constants of thin films makes use of reflectance measurements [41K].

The results based on a new multidimensional model which makes it possible to calculate the spectrally-integrated total radiative flux for a molecular-gas is in excellent agreement with spectrally-integrated results from the P–1 approximation and with some exact results [28K]. The intensities, widths, and position of lines of three CO_2 bands near 3.6 μm have been measured and the results are in general agreement with other measured and estimated values [20K]. Investigations of the effect of dimerization on i.r. absorption in the 6.3 μm band and the total emissivity of H_2O vapor show that the effect is negligible [22K].

The results of a Monte Carlo finite difference method for coupled radiation–conduction heat transfer in semitransparent media are in excellent agreement with results obtained by other methods [1K]. Radiation–natural convection interactions in 2-D complex enclosures are considered taking CO_2 and NH_3 as participating gases into account [12K]. A modified Gardon heat flux probe is described for separate measurements of the components of radiative and convective heat fluxes [27K]. In the wavelength range 3–5 μm the attenuation factors due to CO_2 and H_2O in the atmospheric are 6 and 8%, respectively, at a 10 m range [39K]. Ground based vertical path absorption measurements were made up to a height of 1.5 km with a CO_2 linear transmitting alternatively on the $R(20)$ (10.247 μm) and $R(18)$ (10.260 μm) lines during daylight under conditions of both strong and weak temperature inversions [4K]. Measurements of aerosol and atmospheric i.r. emission spectra show that there is an auroral produced excitation for each band ($CO_2(\gamma_3)$, $NO(\Delta\gamma = 1)$, $O_3(\gamma_3)$ and $CO_2(\gamma_2)$) causing enhancements of $O_3(\gamma_3)$, 9.6 μm, and $CO_2(\gamma_2)$ 15 μm emissions [43K].

The thermal performance of radiative cooling panels has been calculated. Measurements show that, for most applications, white paint is a better radiator than aluminized polyvinyl fluoride films [5K]. Comparisons of equilibrium and nonequilibrium radiative heating studies are reported, associated with heat shield performance during outer planet atmospheric entry [31K].

Studies of radiant heat transfer in fibrous insulations indicate that the radiant heat flux can be minimized by making the mean radius of the fibers close to that which yields the maximum extinction coefficient [46K]. Corresponding experimental studies are compared with these predictions, indicating that the analytical models are useful in giving representative values for the radiative properties of typical light weight fibrous insulations [47K].

A model of radiative heat transfer in a dispersed medium is suggested which allows the calculation of the emissivity of an isothermal fluidized bed, the effective emissive ability of a nonisothermal bed and the temperature distribution near a heat transfer surface in a bed of a certain expansion when the radiative properties of the particles and the heat exchanger are prescribed [7K]. A Monte Carlo method is used for analyzing radiative heat transfer through a randomly packed bed of spheres. Qualitative agreement is shown in comparison with other work which used regular cubic packing, and with experimental data [50K].

The results of a study of the stability of horizontal fluid layers with radiative heat generation for two and three porous plates may be useful for solar applications [19K]. The radiation produced on impact of a high-velocity gas jet on an obstacle has been investigated [21K].

Experimental and analytical studies of the collection of thermal radiation by a semi-transparent fluid layer flowing in an open channel show that the results derived from the multiband model show better agreement with experimental data than those from the Planck mean model, independent of the optical thickness of the fluid [18K]. Numerical procedures based on Hottel's zone method are proposed for rapid solutions of view factors needed for radiative heat transfer [26K].

MHD

The number of publications in this field declined substantially during the past year.

Hydromagnetic flow and heat transfer between two horizontal parallel plates where the lower plate is a stretching sheet and the upper plate is porous have been studied in the presence of a transverse magnetic field [2M]. The response of flow and heat transfer to change of direction of the imposed magnetic field in steady MHD laminar free convection flow past an infinite vertical porous plate has been studied taking Hall effects into account [1M]. MHD flows have been studied, considering a circular cylinder in a channel [4M] and an elliptical cylinder for the case of an inviscid fluid [5M].

The effect of a uniform transverse magnetic field on the free convection flow of an electrically conducting fluid past an infinite vertical plate for both impulsive as well as uniformly accelerated motion of the plate is to increase the velocity field in both cases [3M].

APPLICATIONS

Heat exchangers and heat pipes

A comprehensive list of commercial enhanced tubes for shell and tube heat exchangers has been presented [18Q] and a standardized format of presenting geometric, flow, and heat transfer data for those is proposed. A new parameter is shown [32Q] to facilitate calculations for fins and an alternative to the fin efficiency in the analysis of fins has been proposed [17Q]. The conductivity ratio of the materials for a composite fin determines [9Q] the heat transfer rate and the time response. Experimental results were reported [31Q] of cross flow heat exchangers with tubes of lenticular shape. The performance of multiple parallel disk heat exchangers with radially outward flow is comparable [22Q] to high performance plate–fin surfaces. The conjugated heat transfer problem for the entrance region of laminar pipe flow with temperature variations in the surrounding was analyzed [14Q]. Turning off the flow at the inlet of a corruguated wall heat exchanger increases the heat transfer coefficient [33Q].

The exact solution of the Nusselt model of the cross-flow recuperator is presented [12Q] using the Mikusinski operator. Analytic expressions were developed for the mean temperature difference in multipass cross-flow heat exchangers [24Q]. Computer generated charts of the temperature difference in air coolers have been presented [25Q]. A simplified analysis [37Q] predicts the shell-side flow and temperature pattern in heat exchangers. A number of papers analyze the transient performance of heat exchangers for a step change in inlet temperature [8Q] and a periodic flow heat exchanger [5Q]. The method by Gaddis and Schlünder is used to model the time dependent heat exchanger performance [30Q]. Gas-to-gas cross-flow heat exchangers with neither gas mixed are studied [29Q] in their response to a unit step increase in the entering temperature. The influence of omitting some tubes in finned-tube bundles on their thermal and flow characteristics has been investigated [17Q]. Three papers [16Q, 35Q, 15Q] consider the economic aspects of the heat exchanger design.

Experiment [26Q] and analysis [13Q] are dealing with regenerators.

Laboratory experiments [28Q] clarified boiling heat transfer of Freon 11 in brazed aluminum heat exchangers at low mass and heat fluxes. The heat transfer performance of stainless steel metal fiber sintered surfaces to Freon 11 could be improved tenfold [10Q] over smooth surfaces. Experiment and analysis [2Q] determined the shell-side heat transfer coefficient for steam contaminated with noncondensible gases. The use of air–water mist flow improved the performance of a compact cooling unit for semiconductors from 1.8 to 20 times over the performance of a dry unit [26Q]. A mathematical model [11Q] describes the thermal performance of a wet surface plastic-plate heat exchanger with a change in temperature and humidity ratio of an air flow. A hybrid evaporative condenser built into a cooling tower saves heat transfer area or lowers the condensation temperature [7Q]. An exact analysis [34Q] is compared with the method by Merkel [1925] for a mechanical-draft air–water cooling tower and finds that the later method underestimates the performance from 5 to 15%. A computer code [VERA2D] was developed to describe the fields of air velocity, temperature, pressure, and moisture content in a wet cooling tower [19Q, 20Q].

Fouling processes are classified into five categories [36Q]. Particulate fouling on the gas side of finned tube heat exchangers was found [33Q] to increase the friction factor up to 1.4 to 2.5 times of the clean value, whereas the Stanton number decreased by 10 to 20%. Crystalline fouling studies [37Q] showed that the deposition rate is primarily a function of the supersaturation of the solution.

Experiments determined heat transfer and flow of Nak in a heat pipe with steel wool and metal fiber wicks [23Q]. The maximum heat flux through heat pipes with various cross sections was measured [21Q]. Experiments determined [4Q] turbulent heat and mass transfer in vacuum and gas loaded sodium heat pipes.

General

Advances in modelling turbulence and their influence on heat transfer is discussed [7S]. The effect of polymeric additives on the damping of the wall turbulence and on convective heat transfer was investigated experimentally [8S] for flow through a square channel using the electrodiffusion technique. A numerical analysis [12S] studied flow and heat transfer of polymeric fluids through a circular pipe and found that it depended primarily on the Weissenberg number.

Boiling in a two-phase thermosiphon occurs at low pressure in a pulsed mode [1S] with periods of quiet alternating with explosive evaporation. Periodic heat conduction into a semi-infinite medium with 3-D heat flow originating from a rectangular surface region is handled [2S] through Fourier transforms. Heat transfer to block-like aerodynamic components is enhanced by a factor 2 [13S] by fence-like barriers. The hydrodynamic and thermal situation in a steam-generating tube [14S] and rewetting of the tube by a falling film [8S] are studied experimentally to clarify the process in a loss of coolant accident [LOCA]. A survey of heat transfer problems in air cooled high temperature gas turbines is presented [3S]. Transpiration air-cooled turbine blades showed no evidence of erosion, corrosion, or deposition when exposed to combustion gases carrying solid particles with a temperature up to 1650°C [17S]. The cooling of casings, struts, and disks by steam was studied [10S]. An analysis was concerned with simultaneous transfer of heat and mass in a casting process [12S]. Another analysis [6S] provides a simplified prediction of the melting surface and of heat conduction in electro-discharge machining. The cooling of fibers by natural convection and radiation during the melt-spinning process is analyzed numerically [5S]. The flights of the shuttle orbiter provided the possibility to obtain heat transfer data during reentry [16S, 15S, 9S, 18S]. Generally, turbulent heat transfer and transition location compared well with currently established ways of prediction. Data during the second and third flight were generally lower than wind tunnel results. There were contradictions in the surface emissivity obtained from reflectance and emittance measurements.

Solar Energy

A statistical comparison was made of three solar flux estimating models [25T]. Data sets are presented for the direct normal and global solar spectra, both for Air Mass 1.5 [5T]. The Liu–Jordan model for solar flux has been modified to better account for the effects of altitude and snow cover (i.e. changes in the albedo of large portions of the terrain) [24T]. In developing a solar radiation model, a reasonable estimate of lower layer aerosol extinction can be determined using humidity, visibility, and mixing height [34T]. The spectral distributions of solar radiation at ground surface, computed from extraterrestrial solar spectral irradiance, are presented for several air mass values and for four levels of atmospheric pollution [28T]. The absorption of radiation by molecules such as O_3, H_2O and the uniformly-mixed gas is taken into account in an empirical model for the calculation of solar spectral diffuse and global irradiance under cloudless skys [6T]. A model of the spectral direct radiation of the sun at ground level compared with the spectral measurements performed by a monochromator has evidenced satisfactory agreement [13T]. A model has been developed to calculate the downwelling infrared radiation from a clear night atmosphere using LOWTRAN 5, an atmospheric transmittance/radiance model developed at the U.S. Air Force Geophysics Laboratory [37T]. Classical probability theory is used to derive expressions for the mean values of quantities such as the solar flux on inclined surfaces, collector output, and net gain through windows [17T].

The transient characteristics of a flat-plate solar collector were described [32T]. An efficient algorithm is presented for solving the set of nonlinear equations governing the total heat transfer across an arbitrary number of semitransparent flat-plate solar collector covers [18T]. An approximate calculation of the radiative–conductive flux of heat from the absorber to the cover plate of a flat-plate collector equipped with a convection-suppressing honeycomb is developed using an exponential kernal approximation to the passage transmittance function of the honeycomb cells [26T]. A mathematical model of a collector in which the working fluid passes through successive transparent layers indicates the collector performance is a function of the number of layers, the heat transfer coefficient across each layer and the absorption properties of the fluid [21T]. The single-pass as well as the two-pass mode of heat withdraw from a two-layer thermal trap collector with slabs of variable thermal and optical properties are modelled mathematically [33T]. A computer simulation of a regenerating-type solar collector is presented and optimum ranges of design parameters are indicated [20T]. An air cooled collector that uses a close packed array of evacuated tubes for a cover has been shown to produce high efficiencies at low solar flux levels [15T]. A system simulation study indicated that the collector with a cover made of close-packed evacuated tubes delivered three times more heat than a "typical flat plate" on a seasonal basis [16T]. Measurements are reported for assorted heat removal schemes in single-ended glass tubes with the nonuniform solar input around the tube simulated electrically [41T].

A review is presented of a wide variety of point-focusing solar concentrators that are under consideration for solar thermal energy use [19T]. The theory developed for the utilizability function has been applied to high concentration ratio focusing collectors [12T]. A comparison is made between fluidized and packed bed receivers for high temperature solar gas heating systems [11T]. The maximum efficiency of solar energy conversion devices is investigated [7T].

A finite element heat transport program has been modified to model the thermal behavior of a cylindrically symmetric salt gradient solar pond of the Rabl–Nielsen type [8T]. A computer model is described which may be used for predicting transient salinity and temperature profiles in salt gradient solar ponds which have large surface areas and where wind-mixing is expected to be important [4T]. If the temperature and salt concentration dependency of the thermal conductivity of the water in solar ponds is ignored, very little error is introduced into the thermal characteristics analysis [40T].

An extensive review of heat-of-fusion storage materials for low temperature heat storage (0–120°C) is presented [1T]. The heat and mass transfer characteristics of a thermochemical energy storage system based on solid–gas reactions have been studied through the example of the borax dehydration reaction in an apparatus simulating 1-D heat transfer [2T]. The losses of heat from a seasonal ground storage system due to conduction and natural convection in groundwater have been investigated [39T]. A simplified steady state model to evaluate the effect of floor coverings on the storage of solar energy indicates that even the thinnest of carpets interferes severely with storage in a floor slab [14T].

Based on a Fourier series solution of the heat conduction equation, a mathematical model has been developed to analyze the thermal performance of some typical passive heating concepts [30T]. A design method, based on monthly average temperatures, has been developed to approximate the need for shading and other strategies for passive cooling [31T]. The influences of solar radiation, environmental long-wave radiation and the radiation from internal walls were included in an analytic relation describing the thermal gain of a room [3T]. Thermal storage walls for use in passive solar collectors are analyzed with the purpose of establishing guidelines for the design of low-mass, high-efficiency walls [22T].

Tests conducted at the National Bureau of Standards Test Facility indicate that the performance of a typical solar domestic hot water system is relatively insensitive to various load profiles [10T]. The performance of six thermosyphon solar water heaters was measured while the systems were supplying typical domestic hot water loads [29T]. The thermal performance of an integral compact solar water heater is evaluated experimentally and numerically [36T]. A transient analysis is presented of the performance of a solar water heating system with natural circulation of hot water between the collector and an insulated storage tank which contains a heat exchanger to transfer heat to hot water which would be used for either domestic or industrial purposes [35T]. A transient simulation program is presented for analyzing a solar air heating system which has either rock bed or phase change energy storage [38T]. Simulations have shown that a solar driven absorption heat pump system can supply a significant fraction of a residential heating and cooling load with nonpurchased energy [37T]. A mathematical model for a flat-plate solar system integrated with a storage tank and an organic Rankine cycle loop was to used to determine the optimum flow rate through the collector [9T]. A 10% efficiency was obtained in a solar thermal engine system by augmenting a paraboloidal concentrator with a new type of nonimaging second stage concentrator which is shaped like the bell of a trumpet [23T].

Plasma heat transfer

Plasma heat transfer seems to be of particular interest in connection with arc technology and thermal plasma processing.

Studies of transient heat conduction of particles under plasma conditions reveal that, for example, the surface temperature of a 100 μm alumina particle can reach the boiling point (4000 K) while its center is still in the solid state [2U]. Heat transfer studies to particles immersed into a thermal plasma indicate that the Knudsen effect may play an important role, even at atmospheric pressure [5U]. Studies of the behavior of small particles injected into a thermal plasma flow taking convection into account demonstrate that the ratio of the heat fluxes with and without the Knudsen effect is almost identical to the ratio obtained for the case of pure heat conduction [4U]. Investigations of particle momentum and heat transfer in a thermal plasma show good agreement between measured and computed particle velocities. Measured particle temperatures, however, differ substantially from predicted values [25U].

A mathematical model has been developed for describing fluid flow and heat transfer in the cathode region of high intensity carbon arcs [20U]. An analysis of the cathode region of a free-burning high intensity argon arc reveals that a significant fraction of the total current (up to 18%) is carried by positive ions which is crucial for the heat balance at the cathode surface [14U]. A model for the thermionically emitting cathode of a 100 A argon arc has been proposed. At the very tip of the cathode, the current is predominantly carried by electrons and the surface temperature is determined by the balance of heating by plasma radiation and cooling by thermionic emission [7U].

Studies of the behavior of sustained high-current arcs on molten alloy electrodes during vacuum consumable arc remelting indicate that by introducing CO into the vertical alloy electrode system at larger electrode gaps, the cathode thermal power is reduced by approximately 50% [27U]. Studies of the fusion boundary energy transport during arc welding show that at current levels close to 300 A, significant weld pool convection occurs, especially at the (inner) stagnation point, causing a deeper penetration of the fusion boundary at this location [19U]. Investigations of the power dissipation in the column of a TIG welding arc at pressures up to 135 bar indicate that for a 100 A, 10 mm argon arc, convective dissipation accounts for about 70% of column power at all pressures. Radiation contributes 18% at 1 bar increasing to 26% at 20 bar [1U].

Measured and calculated temperature distributions in free-burning, high-intensity argon arcs show good agreement as long as the cathode tip remains intact [13U]. Calculated temperature distributions of a free-burning, high-intensity arc are in better agreement with measurements if the calculations are based on a two-temperature model [12U]. Investigations of the operating characteristics and energy distribution in transferred plasma arc systems indicate that radiation from the plasma column to the chamber walls and transfer of energy to the anode by the arc current and convection are the principal modes of transfer of the arc energy [6U]. Studies of the characteristics of a transferred-arc plasma show that the amount of energy release at the anode increases substantially with increasing current and power losses by radiation from the arc range between 41% and 53% of the total power input depending on the electrode separation [21U].

Studies of the effects of low-ionization-potential contaminants on thermal plasma show that for sufficiently high plasma temperatures, the behavior is dominated by the high-ionization potential component whereas low-ionization-potential properties determine the low-temperature plasma behavior [16U]. Experimental studies of the electrode vapor flow in a free-burning, pulsed (12.5 kA) arc in air with a Cu-anode and a Cu-W cathode show that the arc column is dominated by the electrode vapor during most of the arcing period [26U]. Investigations of d.c. nozzle arcs with mild wall ablation show that a theoretical model can adequately describe the nozzle arc behavior in the presence of wall ablation [10U].

Experimental studies of anode melting in a multicathode-spot vacuum arc show that peak currents for melting are in the range of 500–2 3000 A depending on the electrode materials [11U]. A new model for the anode spot formation in a vacuum arc is introduced, based on the assumption that anode spot formation is associated with a change of sign of the anode fall (from negative to positive) [9U].

Calculations of the specific heat flux to a cylinder in a thermal plasma cross flow are in general agreement with experimental data in spite of the use of the boundary layer approximation and the potential flow assumption for the outer region in these calculations [3U]. When W rods of 0.203 and 0.3175 cm dia. are exposed perpendicularly to an argon plasma jet up to the middle of the flame, special values of h and T_∞ have to be used in order to reproduce by calculation the measured temperature profiles [22U].

Rapid quenching of air plasma effluents (2350–2600 K) leads to higher nitric oxide concentrations than those predicted from stagnant equilibrium conditions [23U]. Studies of efficacy, arc tube temperature, and power dissipation in a high-pressure sodium lamp show that the proportion of the total radiation emitted in the D-lines decreases as the power input increases. But this is more than compensated by an increase in the total radiated power at the expense of thermal conduction [8U].

Studies of the efficiency and erosion characteristics of plasma jet igniters in I.C. engines indicate that the thermal energy delivered by the igniter to the adjacent gas corresponds to overall efficiencies of ≈ 10% [24U]. Experimental and analytical studies of heat transfer from a thin horizontal wire and large cylinders in a corona wind suggest that the Nusselt number is a function of a new (complicated) dimensionless parameter [18U].

An infrared calorimeter for time-resolved plasma energy flux measurements has been developed with a response time of 12 μs and a peak-to-peak noise equivalent of 0.4 mJ/cm^2 [15U].

An extension of the Spitzer-Härm theory is presented for the case of thermal transport in steep temperature gradients [17U].

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