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Heat transfer—a review of 1990 literature

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INTRODUCTION

THIS REVIEW surveys and characterizes papers comprising various fields of heat transfer that were published in the literature during 1990. It is intended to encompass the English language literature, including English translations of foreign language papers, and also includes many foreign language papers for which English abstracts are available. The literature search was inclusive, however, the great number of publications made selections in some of the review sections necessary.

Several conferences during 1990 were devoted to heat transfer or included heat transfer topics in their sessions. They will be briefly discussed in chronological order in this section. The *Third International Energy Agency Heat Pump Conference* was held in Tokyo, Japan, 12–15 March. Proceedings are available from Pergamon Press. The International Center for Heat and Mass Transfer organized a seminar on *Phase-Interphase Phenomena in Multiphase Flow* at Dubrovnik, Yugoslavia, 14–18 May, with topics including thermal, inertial, and diffusion controlled systems, surface tension, surfactants, and applications. Proceedings are published by Pergamon Press. The *Second Intersociety Conference on Thermal Phenomena in Electronic Systems* in Las Vegas, Nevada, featured a session on heat transfer in electronic devices and packages. The *1990 ASME Turbo Expo* was held in Brussels, Belgium, 11–14 June. Sessions on external and internal gas-side heat transfer, film cooling, heat transfer in rotating components, jets, high temperature materials, and coatings were included in the program. Proceedings can be obtained at the International Gas Turbine Institute, Atlanta, Georgia. The *1990 AIAA/ASME Thermophysics and Heat Transfer Conference* was held in Seattle, Washington, 18–20 June. The Heat Transfer Division papers are published in 14 volumes by ASME. The *8th National Congress on Heat Transfer* in Ancona, Italy, 28–30 June, concentrated on the topics: single and multiphase thermo fluid-dynamics and heat transfer in nuclear and energy systems. Papers presented are published in the journals *Heat and Technology* and *Tecnica Italiana*. The *First International Conference on Advanced Methods in Heat Transfer* in Portsmouth, U.K., 17–20 July, included fire and combustion, electro-magnetic fields, heat and mass transfer, and diffusion in the topics. Conference proceedings are published by Computational Mechanics Publication. The *25th Intersociety Energy Conversion Engineering Conference*, at Reno, Nevada, 12–17 August, included topics like geothermal, solar, biomass, wind, and nuclear energy. Proceedings are available at the American Institute of Chemical Engineers, New York.

The *Ninth International Heat Transfer Conference* was held in Jerusalem, Israel, 19–24 August. The program covered the whole field of basic and applied heat transfer science with the theme 'Classical and Modern Heat Transfer'. It consisted of 32 keynote lectures, 21 poster sessions in which 450 papers were presented, 14 panel discussions, and a number of short courses. The keynote and general papers are available in 7 volumes from Hemisphere Publishing Company. James P. Hartnett was given the 1989 Max Jakob Award, the highest recognition of achievements in heat transfer, Richard J. Goldstein received the 1990 Luikov medal from the International Center of Heat and Mass Transfer, and Richard T. Lahey, Jr. was the recipient of the 1989 Donald Q. Kern award.

The *1990 Cogen-Turbo IV*, the 4th International Symposium and Exposition on Gas Turbines in Cogeneration, Repowering and Peak-Load Power Generation was held in New Orleans, Louisiana, 27–29 August. Keynote and general papers covered research, design, development, operation, and environmental aspects. Proceedings are available at the International Gas Turbine Institute, Atlanta, Georgia and selected papers are published in relevant ASME journals. The *XXII ICHMT International Symposium on Manufacturing and Materials Processing* organized at Dubrovnik, Yugoslavia by the International Center for Heat and Mass Transfer, 27–31 August, provided a forum for review and discussion of recent progress in research. The *International Conference on Applications and Efficiency of Heat Pump Systems*, at Munich, Germany, 18–21 September, considered appropriate heat transfer situations, new working fluids and those for high temperature, control systems and instrumentation. The proceedings of the *Third International Conference on Circulating Fluidized Beds* at Nagoya, Japan, 14–18

October, published by Pergamon Press, lists a number of contributions on heat transfer and hydrodynamics. The *First Thermal Structure Conference* was organized by the University of Virginia and held at Charlottesville, 13–15 November, with the goal to address the features of integrated design and development of thermal structures. The *1990 ASME Winter Annual Meeting* held at Dallas, Texas, 25–30 November, included 39 sessions on heat transfer with topics such as fundamentals of micro heat and mass transfer, and heat transfer in gas engines. Panel sessions discussed directions and issues in heat transfer and research needs in direct combustion among other topics. The papers presented are available in special volumes from the ASME order department. The *Third Brazilian Thermal Science Meeting* at Itapema, Brazil, 10–12 December, featured lectures on recent advances in thermal comfort and transport phenomena in metals processing among approximately 200 papers and a number of mini-courses.

A list of books related to heat transfer and new journals published during 1990 is presented on the following pages. To facilitate the use of the review, a listing of the subject items is made below in the order in which they appear in the text. The letter which appears adjacent to each subject heading is also added to the references cited in each category.

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CONDUCTION

Research issues in the category relevant to conduction heat transfer conducted this past year are overviewed in this section. The associated subcategories encompass contact conduction/contact resistance; composite or layered media; laser pulse heating/wave propagation phenomenon; conduction heat transfer issues associated with fins, rods, tubes, spheres, etc.; conduction heat transfer influenced by convection and/or flow effects; analytical, approximate/numerical methods and algorithms; thermomechanical issues; inverse problems; applications to electronics packaging; and miscellaneous applications.

Contact conduction/contact resistance

Experimental and theoretical investigations encompassing contact conduction and contact resistance related problems are identified in this subcategory. The investigations included contact conductance in composite cylinders, periodic contact of surfaces, measurement of contact conductance in anodized aluminum coatings, issues related to contact conduction and resistance in turned surfaces and bolted/riveted joints, contact conductances at low applied loading situations, contact resistance in finned tubes, etc. [1A–9A].

Composite materials and layered media

Problems in this subcategory involved steady and transient heat conduction in anisotropic composite media, heat transfer in orthotropic cylinders and plates due to various boundary conditions, and conductivity of n-dimensional composites influenced by hyperspherical inclusions [10A–19A].

Laser/pulse heating and related problems

Laser heating effects on droplets with an absorbing core, micron-sized droplets irradiated with a pulsed CO_2 laser and time evolution of caustics of a laser heated liquid film appear in refs. [20A–22A].

Heat conduction in fins/tubes/rods/spheres/cylinders

Solutions to conduction heat transfer in fins, effect of thermal conductivity in rectangular fins, and transient response of spiral fins subjected to sinusoidal temperature appear in refs. [24A, 23A, 25A]. An analytic method for computing heat power through rods and composite slabs appears in ref. [26A].

Conduction influenced by convection and/or flow effects

Papers appearing in this subcategory involved temperature distribution in a semi-infinite body with exponential source and convection boundary condition, effects of wall thermal resistance in forced convection around two-dimensional bodies, numerical simulation for a valve flow-field region for a four-stroke piston engine, and thermal heat conduction in cellular structures containing a well-stirred fluid or a perfect conductor [27A–30A].

Analytical, approximate/numerical methods

There seemed to be a significant amount of interest involving development of analytic solution methods and numerical simulations for various heat conduction problems. Much of the work involved new and innovative numerical solution approaches, closed-form solution of specific problems, and also approximate techniques. Heat conduction effects due to various boundary conditions were also attempted. All of these are identified in refs. [31A–61A].

Thermo-mechanical problems

Thermo-mechanical effects play an important role in materials and structures which are influenced by thermal effects. The so-called field of thermal-stresses is an important concern in various fields of engineering and mathematical/physical sciences. Typical problems may involve elastic, elasto-plastic, or elasto-viscoplastic material behavior under the influence of thermal effects. Transient problems may involve thermally-induced wave propagation or thermal-structural dynamic problems. Papers dealing with thermo-mechanical problems appear in refs. [62A–76A]. Other related applications are included in the subcategory on electronics packaging which follows next.

Electronics packaging

Papers in this subcategory address various thermal, and thermal-stress issues encountered in applications related to electronics packaging. These appear specifically in refs. [77A–89A].

Inverse problems

Inverse models and formulations are important in certain applications where not all of the information is available to solve the direct problem. For example, whereas temperatures may be known at certain selected locations within a body, the corresponding boundary conditions may be unknown. Such problems necessitate the use of inverse methods for solving them. Papers dealing with inverse problems are included in refs. [90A–97A].

Miscellaneous heat conduction problems and special applications

Numerous other papers involving various aspects of heat conduction appear in refs. [98A–131A].

BOUNDARY LAYER AND EXTERNAL FLOWS

The research on boundary layers and external flows during 1990 has been categorized as follows: flows influenced externally (by vibration, rotation, vortex generators, interaction with the wall, etc.); special geometry effects; high-velocity, high temperature flow effects, including shocks or dissociation; papers stressing analysis or modeling techniques; flows with unsteady effects; films; and flows with special fluid behavior.

External effects [1B–24B]

Experiments were made with vibration of a sphere, cylinder or tube and enhancement of heat transfer was correlated with fluid mechanic dissipation. Another study was with rotation of a disk in a fluid influenced by an electric field. Several papers emphasized the influence of heat conduction in an adjacent solid; longitudinal heat conduction in a flat plate, in a continuously-moving sheet and in a stretching sheet. In a related paper, the solid surface was disintegrating.

Numerous papers showed the influence of body and pressure forces. Two of them were on mixed convection on a horizontal plate and natural convection on the outside of an insulated pipe. Magnetic fluid coatings for boundary layer separation control and electric field application for frost control were demonstrated. The effects on heat transfer of the flow field of counter-current wall jets, buoyant wall jets, horseshoe vortex structure (including jet engine endwall flow), streamwise pressure gradients (including that generated by a piston), and cross-stream pressure gradients due to curvature were demonstrated.

The influences of thermal conditions such as chemical reaction, steps in wall temperature or heat flux or sudden or cyclic heating of the wall were discussed.

Geometric effects [25B–55B]

Papers in this category focus on special effects due to the global geometry or surface geometry. Numerous papers were given on heat transfer from geometries with stagnation points such as circular and rectangular cylinders (including wires). One dealt with flow over slender cones. Another featured viscoelastic flow past a cylinder. Several featured the flow near a cylinder-to-wall junction, one included conduction in the solid elements for a pin geometry.

The influences of surface features, ranging from corrugations, to ribs (some twisted), protruding and heated elements and heat sinks, spherical depressions or bumps, delta-wing vortex generators, large eddy breakup devices and hair were assessed. Two papers dealt generally with complex surface shapes and another with particle shapes.

Compressibility and high-speed flow effects [56B–72B]

A topic of continued interest is high-speed flow. Numerous papers investigated the special effects of shocks. One was on thermal shock due to energy accumulation near a rapidly-moving heat source. Several were related to space shuttle and other high-speed flight surface heating. Some dealt with non-equilibrium effects or dissociation in the fluid; one dealt with surface cooling effects. A number of papers in this topic focused on geometry, such as nose shape, which influences the nature of the flowfield. Many of the papers in this category included radiation effects.

Analysis and modeling [73B–83B]

With the increased reliance on computation, numerous papers presented development of computer models and analyses. Such modeling activity included near-wall model development for turbulent heat flux and flowfield modeling of eddy viscosity and turbulent Prandtl number. One was specific to convective atmospheric boundary layers.

Analyses were given for a blunt plane plate, flow between a plate and liquid metals, flow around submerged objects and separated flows. One analysis investigated entropy production in boundary layers.

Unsteady effects [84B–98B]

Several of the papers in this category specifically studied the unsteady flow in turbines, such as the effects of passing wakes from upstream airfoils. One presented a computational model, another showed the wake effect on stagnation region heat transfer.

Another group of papers was on unsteady heating of the solid. One studied hot spot formation prior to boiling, others were on temperature fluctuation in particles, drops and sprays, and another investigated the instability of flow over a horizontal flat-plate leading to longitudinal vortices. Unstable flow was also induced by regular, three-dimensional structures on a plane and by saw-tooth grooves in a channel to enhance heat transfer. An analysis of such unsteady flows was presented. The effects of elevated free-stream turbulence were experimentally assessed with focus on the sensitivity to turbulence-generating grid design.

Films [99B–104B]

Studies on liquid film heat and mass transfer in the 1990 literature included effects of multiple components, evaporation, and local heating.

Fluid types [105B–107B]

Papers specific to fluid type were on heat transfer to spheres in a polymer melt and to micropolar fluids with stretch on a sheet or near a stagnation point.

CHANNEL FLOWS

Forced convection in ducts represented a significant fraction of heat transfer research in 1990. The relatively simple boundary conditions imposed by these internal flows allow for convenient validation of various numerical schemes. A perusal of the literature indicated that an overwhelming majority of the research was of an analytical/numerical nature (70%). Channel flow research was subdivided into the following categories: straight-walled circular and rectangular ducts; irregular geometries; entrance effects; oscillatory and transient flow; finned and profiled ducts; duct flows with swirl and secondary flow; two-phase flow in ducts; miscellaneous research including non-Newtonian fluids, flow of liquid helium, and lubrication.

Straight-walled circular and rectangular ducts

The ubiquitous nature of straight-walled circular and rectangular ducts continues to provide ample motivation for fundamental research under both laminar and turbulent flow conditions [1C–17C]. Several papers were concerned with the effects of axial wall conduction on the heat transfer characteristics in tubes; neglecting axial wall conduction can lead to significant errors in heat transfer prediction for low Prandtl number fluids such as liquid metals. Axial and radial turbulent heat fluxes were predicted in circular ducts under fully turbulent, transitional, and relaminarizing flow conditions; some comparisons with experimental data were made. Heat transfer and corresponding pressure drop penalties were measured under supercritical and pseudo-critical conditions in smooth-walled channels; in one configuration the effect of gravity on turbulence reduction in vertical ducts was examined. A theoretical justification for the viscous correction formula in pipe flows was provided; both heating and cooling configurations were addressed.

Irregular geometries

Forced convection heat transfer in annular straight-walled ducts represented the majority of irregular geometries in the open literature. Numerical studies in annular passages provided an examination of several unusual boundary conditions including: suction/blowing on inner and outer walls; impermeable walls; axially translating core; countercurrent flow in annuli with uniform heat generation. Relaminarization of strongly heated gas flow was compared in circular ducts and concentric annuli. One study considered the flow of liquid metals in eccentric annuli. Straight-walled ducts of semi-circular, right-triangular (15°, 30°, and 45°), and slightly noncylindrical cross section (e.g. to model deformed walls) were computed under laminar flow conditions with uniform wall temperature boundary conditions. Symmetric radial gap flow was investigated as a model for electro-organic synthesis. Axial flow in ducts along triangular and square arrays of circular cylinders was computed numerically; heat transfer rates were higher for the triangular arrangements [18C–28C].

Entrance effects

The vast majority of forced convection heat transfer in practical devices occurs under thermally developing conditions—seldom are we afforded the luxury of establishing fully developed flow in the complex passages of heat exchangers, turbine blades, or between printed circuit boards. In fact, the designer often uses the developing flow to achieve heat transfer augmentation. Research included in this category focused on fundamental studies of thermally developing flow in straight-walled ducts of circular, rectangular, and circular-sector cross sections; typically fully developed hydrodynamic conditions were assumed [29C–39C]. A variety of numerical schemes were employed to obtain laminar flow solutions including the method of lines, vorticity–velocity formulations, finite differences, and a novel approach which predicted the thermal entrance length without solving the complete entrance length problem. Buoyancy effects were considered in the entry region of horizontal rectangular channels. One study computed the effect of the temperature dependence of viscosity on the heat transfer rate.

Oscillatory and transient flow

Time-dependent forced convection heat transfer in ducts was examined in the literature in two broad areas: flows with time-varying boundary conditions (e.g. periodic forcing), and impulsively started flows including those which were hydrodynamically developed but experienced step changes in the thermal loading [40C–53C]. Peristaltic transport common in heart–lung machines was modeled by solving the Oberbeck–Boussinesq equations. A periodically-varying inlet temperature was imposed on fully-developed laminar flow in circular and rectangular ducts. Oscillatory flow induced by Tollmien–Schlichting waves was numerically investigated in grooved and communicating channels. Arbitrary time-variations of the axial pressure gradient were imposed on laminar channel flow; detailed results were presented for the case of linear variation. The heat transfer augmentation due to thermoacoustic oscillations was examined in a combined numerical/experimental investigation. Step changes in thermal loading were studied in a variety of situations including: step changes in wall temperature in fully-developed laminar flow; thermal start-up in long pipes; mixed convection in pipe flow subjected to direction change from descending to ascending.

Finned and profiled ducts

Heat transfer augmentation in finned channels often comes at the expense of additional pressure drop penalty. Research in this category addressed both of these issues in a variety of geometric configurations, and was approximately equally divided between experimental and numerical work [54C–68C]. Discrete and in-line arrays of protruding heat sources were examined under laminar, mixed convection, and transitional flow conditions; under certain conditions heat transfer could be enhanced and pumping power reduced by reductions in the flow rate. Internal longitudinal finning was investigated under laminar flow conditions with constant wall temperature and constant wall heat flux boundary conditions. Staggered and in-line arrangements of longitudinal finning having periodic interruption in the streamwise direction were examined; staggered longitudinal finning produced less heat transfer than a tube with continuous finning for $Pr = 0.7$. Baffled passages of heat exchangers were studied for rectangular, circular, and annular geometries. Internal helical finning was studied and found to behave much like twisted-tape inserts. The heat transfer characteristics of knurled pipes and those with discrete roughness elements were investigated experimentally.

Duct flows with swirl and secondary motion

Swirl motions superimposed on longitudinal flow in straight-walled ducts received considerable attention in the literature. One common method of generating swirl is by the placement of twisted-tape elements along the duct; experimental and numerical results indicate that regularly spaced elements did not perform better than full-length twisted tapes. Tubular lances were employed to generate a swirl motion in an annular duct; heat transfer and pressure drop penalty were considered. A swirling motion set up by rotating the inner cylinder of an annulus was examined experimentally using a sublimation technique; strong rotation rates gave rise to Taylor vortices. The motion of swirling gas–liquid eddies was measured using an electro-contact method. Thirty-fold increases in heat transfer rates were established by superimposing swirl at the inlet to a vortex generator. Swirling flow in a 19-rod bundle was also investigated. The secondary motion of fluid due to centripetal acceleration can also lead to heat transfer augmentation. Helically coiled pipes were studied under a variety of situations: at supercritical pressures; as a function of the steepness of the coil; in thin-walled pipes at high heat fluxes; in the presence of synthetic roughnesses [69C–83C].

Two-phase flow in ducts

The heat transfer characteristics of gas–solid, liquid–solid, gas–liquid, and dissimilar liquid systems appeared in the literature [84C–98C]. Material/thermal interactions were examined in a gas–solid flow using the method of inverse conduction. Electrically charged glass particles in air were studied experimentally in a vertically oriented turbulent pipe flow; the electric field could be used to enhance the heat transfer rate. The turbulent flow of dusty gas was studied in the presence of convection and radiation. Liquid–gas systems were investigated under the following conditions: variation of flow direction in vertical tubes; effect of gravity field on flow in helically coiled pipes including the effect of inclination angle; the effect of properties of 21 different fluids in vertical and horizontal channels (including organics, freons, cryogens); mist flow in circular and annular ducts. The influence of inclination angle on solidification in rectangular channels was studied experimentally; longitudinal vortices produced grooves in the solid surface. The coflow of immiscible liquids was used to study the transport of very viscous fluids in pipes.

Miscellaneous studies

Several studies in the literature did not conveniently fit into one of the categories reviewed above [99C–117C]. Non-Newtonian fluids (e.g. power-law fluids, epoxy resin) were examined in the entrance regions of ducts and in a single-screw extruder. Liquid helium flow was studied in porous tubes as well as under conditions of forced and mixed convection in vertical channels. A review of recent advances in the Soviet research of liquid helium flow also appeared during the year. A number of thermo-hydrodynamic studies in lubricating channels appeared in the literature. The heat transfer in channels with porous inserts was also investigated.

FLOW WITH SEPARATED REGIONS

Isolated cylinders and arrays of cylinders were the most common separated flow configurations examined in the heat transfer literature; a small number of studies investigated the thermo-hydrodynamics of backward-facing step flow as well as heat sources subjected to fluid shear.

Flow over an isolated cylinder

The flow past a single cylinder in crossflow becomes unstable at very low Reynolds numbers, giving way to the famous Kármán vortex street. The dynamics of the vortex shedding process are affected by a variety of boundary conditions including cylinder vibrations, end effects, and flow non-uniformity. These effects can lead to significant three-dimensionality and corresponding alterations in the heat transfer rate between the cylinder and fluid. Flow over an isolated cylinder was examined in the following studies [1D–7D]: downward flow of air–water mist past a circular cylinder; forced convection from a nonisothermal cylinder; local heat transfer measurements from a circular cylinder located downstream of a row of cylinders; time-resolved measurements of total temperature and pressure; heat transfer measurements of the flow past a coiled wire; a study of the thermal wake of a hot wire near conducting and non-conducting walls in laminar flow.

Flow through multiple cylinder arrangements

The separated flow and heat transfer from multiple cylinder arrangements (e.g. tube bundles) was also examined in the literature [8D–21D]. Circular pin fins were used to enhance the heat transfer rate in the passages of turbine blades. The pressure drop and heat transfer associated with the flow downstream of wall-pin configurations were studied. Tube banks were investigated in a variety of geometries; both single- and two-phase flows were considered.

Flow past a backward-facing step

Flow past a backward-facing step was treated in a few studies, including mixed convection in the separated region, the effect of pressure gradient on the flow, and the nature of the turbulent structure within the separated region [22D–25D].

Flow with a line source of heat

The effect of fluid shear on the dispersion of a line source was also considered [26D, 27D].

HEAT TRANSFER IN POROUS MEDIA

Porous media is broadly considered in this section to represent either a continuous solid having interconnected pores, or a discontinuous solid with intergranular cavities, through which a fluid phase or phases may flow. With numerous small pores or cavities, enormous extents of interfacial area can be exposed within a small volume.

Packed beds (forced convection)

In many applications the solid material is held stationary, even though it may be unconsolidated, while an externally imposed pressure gradient forces a fluid to flow through it. Basic studies on packed bed inter-phase heat transfer included a correlation for volumetric heat transfer coefficients using a characteristic length determined from the pressure gradient [7DP], derivation of a thermal dispersion conductivity tensor [11DP], a theoretical evaluation of a channel entry length [12DP], a numerical simulation of transient inter-phase energy and momentum transfer [22DP], and an experimental study including visualization of boiling due to inter-phase heat transfer [5DP].

A new method was proposed [23DP] for evaluating the maximum radial temperature in a cooled tubular reactor. Heat transfer coefficients at the walls of packed beds were numerically explored [10DP], discussed and clarified [21DP], and measured experimentally [6DP]. Heat transfer at immersed surfaces in packed beds was theoretically examined for flat plates [13DP, 14DP] and experimentally studied for axially aligned cylinders [15DP]. An analytical representation of heat transfer in a packed bed energy storage system was presented [17DP] and the effects on such systems of the storage medium properties [1DP] and wall temperature [2DP] were numerically explored.

Theoretical studies of non-adiabatic catalytic reactors examined stationary states and critical conditions [4DP] and structures for catalyst distribution [18DP]. Heat transfer effects in porous radiant burners were explored [8DP, 9DP, 19DP, 20DP, 24DP]. Other packed bed studies examined the thermal effects of the deformation of a packed bed [16DP] and the heat exchange of a packed bed with a through-flowing gas–solid suspension [3DP].

Packed beds (natural and mixed convection)

Although natural convection is directly addressed in Sections F and FF of this review, thermally induced buoyancy may also drive fluid motions in porous media: reports cited in this section are those for which the porous medium plays a major role in the natural convection behavior. Analyses were reported for convection: from an embedded point source [25DP], from a suddenly heated vertical plate to a non-Newtonian fluid [30DP], to a vertical wall with an arbitrary temperature distribution [40DP], from an isothermal vertical plate embedded in a thermally stratified porous medium [41DP], above a nearly horizontal, uniform heat flux surface [31DP], and to a horizontal surface [36DP]. Analyses were also reported for natural convection in horizontal rectangular channels [37DP] and between concentric inclined cylinders [43DP].

Natural convection with evaporation in porous media was explored analytically for buried nuclear waste package assessment [29DP] and for near critical point conditions to model geothermal systems [28DP]. Dryout heat fluxes for water–ethanol mixtures were measured for screen wicks [38DP] and natural convection melting of frozen porous media was explored both experimentally and numerically [27DP]. Experiments measured the exposed free surface temperature of a heated porous medium, corroborating a model using Cauchy boundary conditions on exposed surfaces suggested for monitoring the self-heating of coal piles [26DP].

Analyses of mixed convection were reported for horizontal isothermal surfaces [39DP], vertical surfaces exposed to a fluid with variable viscosity [34DP], inclined surfaces with lateral mass fluxes [32DP], horizontal surfaces with surface mass fluxes [33DP], slender bodies of revolution [35DP], and a radially rotating semi-porous channel [42DP].

Onset of natural convection and instability

Several studies dealt with transitions in natural convection within a horizontal porous layer; they examined the effects of a localized inhomogeneity in boundary conditions [52DP], the influence of temporal variations in the imposed temperature gradient [55DP], the influence of non-Darcy flow formulations on transition behavior [45DP, 49DP], the effects of a non-uniform gravitational field [54DP], the effect of a horizontal translational flow on stability [44DP], and the transition behaviors for water saturated porous media at temperatures near water's temperature of maximum density [48DP]. Experiments and visualization supported the suggestion that lateral thermal dispersion explains the multivalued heat transfer measured in horizontal layers of porous media [50DP].

Transitions were also examined in other geometries: a cube [56DP], a layered horizontal slab [53DP], a vertical layer [46DP], and also rectangular horizontal ducts [47DP, 51DP, 57DP].

Non-Darcy effects

Many analyses focused on the use of models for flow resistance that extend beyond the simple isotropic viscous Darcy model, which has been shown to be inadequate at high velocities, with highly porous media, and also when significant voidage variations exist near bounding surfaces. Influences of the Forchheimer, or 'porous inertia', term were explored for a variety of forced, free, and mixed convection cases [62DP–64DP, 66DP, 67DP]. Boundary effects of Brinkman friction were treated in two natural convection cases [59DP, 69DP], and combinations of the non-Darcy effects were employed in several other studies [58DP, 60DP, 61DP, 65DP, 68DP].

Fluidized beds

With sufficient fluid drag, or with other force effects, beds composed of unconsolidated particles can become fluidized, enabling motion of the solid media as well as the surrounding fluid. Much engineering interest continues in the fluid–solid inter-phase heat transfer and the heat transfer from the combination of the fluid with solid particles to containing walls and immersed surfaces.

Fundamental studies of the mechanisms of heat transfer between fluidized beds and contacting surfaces examined particle–surface contact resistance [87DP], maximum possible conduction rates [77DP], particle motions in agitated particle systems [88DP, 89DP], predictions of particle–surface contact time [81DP], heat transfer models using modeled particle contact parameters [90DP, 92DP], and a model of heat transfer through a region of locally high porosity adjacent to a heat transfer surface [78DP].

Experimental approaches were described for measuring the particle pressure at surfaces of fluidized beds [80DP] and for heat transfer in fluidized beds employed to freeze large food items [98DP]. Experiments also explored heat transfer characteristics of horizontal cylinders immersed in fluidized beds, focusing on local behavior around a single cylinder [85DP], heat transfer from a tube with frosting [101DP], and heat transfer for a tube bundle [82DP].

Turbulent, or fast, fluidized beds commonly have equipment to return or circulate particles that have been entrained and transported out of the bed. Models [71DP, 100DP, 103DP] and experiments [71DP, 84DP, 93DP] for heat transfer from such circulating fluidized beds were presented, as were experiments concerning heat transfer in cyclone separators [70DP, 104DP] which may be used to collect and return the particles.

Radiative heat transfer plays an increasingly significant role in fluidized beds at higher temperatures. Effects of high temperature on the fluidization behavior [94DP] as well as on the heat transfer [79DP, 83DP] were experimentally investigated. Heat transfer characteristics of fluidized bed combustors, in particular, were discussed [73DP, 99DP].

Experimental results were presented for heat transfer in three phase (gas–liquid–solid) fluidized beds [86DP, 102DP] and in bubble slurry columns [95DP, 96DP]. Heat transfer characteristics of electrodynamic fluidization, wherein particles are supported by electrical forces rather than fluid drag, were explored [74DP–76DP]. Other studies examined heat transfer in fluidized bed cooling towers [97DP], in fluidized bed steam drying [72DP], and in a fluidized bed technique for soil clean-up [91DP].

Combined heat and mass transfer in porous media

Predominant among the studies in this section are those dealing with removal or addition of water. Moisture content was evaluated experimentally for sintered matrices of spheres [124DP] and numerically for capillary bodies [113DP]. Models of unsteady heat and mass transfer were presented [110DP, 114DP, 115DP, 120DP, 122DP] with some experimental data for cases ranging from forced flow through porous slabs [122DP] to vacuum drying with mechanical agitation [114DP]. Removal of vapor from a through-flowing gas stream was examined [106DP, 119DP, 123DP, 125DP]. Natural convection heat and mass transfer were explored for a sphere [111DP] and a vertical cylinder [131DP] embedded in a porous medium.

The effects of infiltration, especially of moisture, in porous insulation materials were explored [127DP, 128DP]. The assistance of dielectric heating added to convective drying of porous materials was examined [109DP, 116DP]. Discussion of specific applications of combined heat and mass transfer in porous media included fuel cell modeling [112DP], models of metal-hydride beds [107DP, 126DP], models of food drying [105DP, 121DP], moisture transport in clay barriers [130DP] and in soil [108DP, 117DP], simulation of high temperature drying of wood [118DP], and characteristics of steam moisturizing of granular materials [129DP].

Other porous media studies

Several other studies of porous media heat transfer appeared in the literature [132DP–151DP]. Of these, most were unique, addressed to very specific applications, geometries, or boundary conditions. Seven reports focused on predictive models for thermal conductivity [133DP, 134DP, 136DP, 137DP, 145DP–147DP], while two studies examined radiative transport through packed spheres [138DP, 139DP].

EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

Studies involving experimental work in heat transfer are represented throughout this review; this section addresses those studies for which the primary emphasis is innovation or improvement in methods or instruments. Seven separate techniques are briefly, but usefully described in one report [1E].

Heat transfer measurements

Measurements of the rate of heat transfer or heat flux are the concern of many studies [2E–22E]. Holographic techniques were described [8E, 11E, 12E], the last of which promoted the use of self-developing optical crystals as a nearly instantaneous, permanent, re-usable storage medium. An electromagnetic device for measuring heat fluxes in oceanographic studies was described [17E]. A thermopile local radiation flux meter was described for use within a cylinder immersed in a fluidized bed [2E]. Many studies examined accuracy expectations for measuring transient heat fluxes from thin film gages or with inverse conduction solutions dependent upon internal thermocouples. Other reports explored contact heat transfer, heat leaks through electrical power leads, and heat flux evaluation from thermal indicator coatings.

Temperature measurements—thermocouples

The thermocouple, ubiquitous in heat transfer experimentation, is perpetually challenged to measure temperature more accurately, more quickly, in a more hostile environment, or in a less obtrusive manner. Six reports [23E–28E] documented how some of these challenges have been approached.

Temperature measurements—other techniques

Other temperature indicators must be employed in many circumstances. Two reports dealt with special-purpose resistance thermometers [34E, 38E], and others discussed a very sensitive thermistor bridge [46E], an intrinsic optical fiber sensor [30E], chiral nematic liquid crystals [47E], and aqueous thermo indicator solutions [41E]. Several techniques of infrared thermometry and thermography were presented [33E, 37E–39E, 44E, 45E, 49E, 50E, 52E, 53E]. Optical techniques described included holographic tomography, CARS, laser-induced fluorescence, and speckle photography, including a technique capable of simultaneously measuring temperature, density, and velocity [43E].

Velocity and flow measurements

The frontiers of accuracy and applicability continue to be advanced for hot-wire anemometry as they are for thermocouples. Calibration techniques, temperature compensation, and multi-wire arrangements were described [56E–60E, 62E, 67E, 69E]. Laser Doppler techniques are described for volumetric flow rate measurement [55E] and for multi-component velocity measurements with a single frequency processor [61E]. Other techniques reported include pulsed particle image velocimetry, surface-mounted thermal and electromagnetic flow sensors, and a rotameter designed to give electric as well as visual flow rate indication.

Concentration measurements

Concentration measurement of chemical species through laser induced fluorescence, and concentration of phases in two phase flows by optical and electrical capacitance techniques were described [70E–72E].

Property measurements

Many reports detailed experimental determinations of thermal properties, particularly thermal conductivity. Methods described for measuring the conductivity included X-ray dilatometry, an unsteady hot-wire method, establishment of a plane bicalorimeter, fabrication of a spherical test cell, measurements for protective coatings, and analysis of temperature sensor installation errors [74E–77E, 80E–84E, 90E]. Thermal diffusivity measurements were discussed which used the dilatometry of a solid sample [87E], the phase shift of oscillating temperatures for solids and fluids [89E], and a laser pulse technique for diamond films [73E]. A high speed differential interferometric technique was described for measuring gas density in two-dimensional flows [78E].

Visualization techniques
Four reports focused on methods of rendering thermal-fluid phenomena visible for improved understanding [91E–94E].

Other experimental methods and instruments
New sensors and sensor fabrication techniques were described [99E, 105E, 107E, 110E], and improved optical techniques were outlined [95E, 101E–104E, 108E]. Among a few other reports, one conveyed the potential for acoustic effects to interact in non-obvious ways with the results of heat transfer experiments [111E] and another proclaimed the utility of using cryogenic wind tunnels to explore large Rayleigh number natural convective effects while avoiding the need for large corrections for radiative heat transfer [98E].

NATURAL CONVECTION—INTERNAL FLOWS

Horizontal layers heated from below
Convection in horizontal layers heated from below continues to be of great interest [1F–19F] not only to engineers, but also to a number of researchers in basic and applied sciences including physics, astronomy, meteorology, and geology. Much activity in this area comes from those interested in non-linear phenomena, studying the evolution of flows from simple to complex forms.

A number of studies consider instabilities and transitions in Rayleigh–Bénard convection. These papers include a Galerkin formulation of the three-dimensional equations to predict the onset of flow, the influence of the thermal properties of the bounding walls as occur in cryogenic studies, and critical Rayleigh numbers in a simulation of time-dependent convection in low Prandtl number fluids. Some other studies consider the influence of thermal radiation on instability and the transition from two- to three-dimensional planforms for high Prandtl number fluids. Still other works consider transitions and bifurcation in fluid in a vertical cylinder, and instabilities in open-ended cavities. One analysis covers the convective instability of a ferrofluid in a strong magnetic field; another shows the influence of the interaction of convection and a magnetic field in a stellar body. An experimental study shows the influence of Rayleigh number on the preferred wave number in roll convection. Transitions at low Prandtl number and in a horizontal rectangular channel have been studied analytically. Other studies at moderate and high Rayleigh number include theoretical and numerical studies for flow in finite domains, and flow of a compressible gas.

At large Rayleigh number, the flow becomes unsteady and chaotic, potentially turbulence is established. Experiments at high Rayleigh number include the use of an electrochemical mass transfer technique to determine the asymptotic dependence of the Sherwood (Nusselt) number on the Rayleigh number for a high Schmidt (Prandtl) number fluid, and the use of oil droplets to study large scale motion. A model, which partly simulates building convection has been postulated. An asymptotic analysis describes large scale flow for convection in layers with poorly conducting boundaries.

Miscellaneous studies in horizontal layers
Many other studies [20F–32F] involve buoyancy driven flows in horizontal layers. Several consider convection in horizontally finite containers; these include infinite Prandtl number convection in a cube, numerical simulation of flow in a vertical cylinder and transient convection in a parallelogram-shaped enclosure. Still other studies consider convection in fluids with volumetric energy sources including transient phenomena and compressible flows. Related studies are concerned with layers which have various heat flows in and out at the upper surface. The influence of magnetic fields, convection in a ferrofluid and flow of temperature-sensitive magnetic fluids have been reported. Transient convection in an enclosure up to steady state flow, and the influence of time varying gravitational fields have been examined.

Double-diffusive flows
The density variation driving the flow in a body force field may be due to variation of more than one property. Often the density variation is due to temperature differences; however, in mass transfer driven flows, concentration differences provide the density variation. In a number of systems, both temperature and concentration may vary resulting in what is called double-diffusive convection. Studies of such flows [33F–46F] cover a wide variety of phenomena including convection in a number of different geometries and in packed columns, the influence of lateral heat transfer, as well as variations in the direction of the body force vector, flow in liquids close to saturation, flow through membranes, transient double-diffusive convection, stability of salt-fingers formed in such flows, applications to heat pipes, and even triply diffusive flows.

Marangoni—thermocapillary flows
Convection can be driven not only by body forces, but also by variations in surface free energy across an open or free bounding surface of a liquid. Such flows are called thermocapillary or Marangoni flows. They generally occur in thin layers of fluid often with overlapping effects due to density differences across the layer. Recently, there has been a significant increase in interest in such flows partially due to interesting analytic approaches that have become available for studying them, and also due to their occurrence in a number of applications including crystal growth, welding, and other processes in which there is a molten layer and a free surface. A large number of analytical

and some experimental works were reported in the past year [47F–70F]. Analyses include consideration of stability and exchange of stability, and the resulting destabilized thermocapillary flow. The wave number shortly after the onset of flow has been described. Experiments indicate the presence of a layer where buoyancy driven forces are also important. Numerical studies consider low Prandtl number flows in square and rectangular cavities, the influence of local heating, the differences which occur with wetting and non-wetting liquids, and flows in long rectangular cavities and capillaries with bubbles. Other studies consider oscillatory flows, a column heated locally, flow in a rotating sphere and in two superposed immiscible liquid layers. A number of studies specifically look at float-zones in the crystal-growth process.

Inclined layers, vertical ducts, differentially heated layers

Studies of convection in inclined layers [71F–96F] include visualization of longitudinal convection rolls in a liquid heated from below, and flow in a high-aspect-ratio inclined rectangular duct. Several studies consider heat transfer in differentially heated layers. This might be a vertical duct in which there is a temperature difference between two opposite walls, i.e. one heated, the other cooled. Works reported recently include the stability of convection in a square cavity, incipient flow in a vertical cylindrical annulus, potential of secondary convection in a vertical layer between parallel plates, and the influence of Prandtl number on such flows. The transition to unsteady flow in a water-filled cavity, and convection in water in a vertical annulus have also been considered. The influence of a stably stratified fluid held between vertical plates and the potential of multiple and unsteady solutions in a tall cavity as well as the effect of inlet conditions on free convection flow in a vertical channel were reported. An analysis predicts the minimum heat transfer across a laterally heated vertical slot. Convection of a non-Newtonian fluid held between two concentric vertical cylinders and flow in a simple cylinder have been considered. Applications of such flows to cooling of nuclear power fuel elements have been reported. The influence of wetted walls, of baffles, and honeycombs on convection in vertical ducts can be quite significant.

Horizontal circular tubes and annuli, and spherical shells

Analytical and experimental studies on convection in horizontal circular tubes and annuli, and spherical shells have been reported [97F–111F] for various boundary conditions and ranges of flows. Velocity and temperature profiles have been measured in a differentially-heated annulus, while steady multicellular flows in such a geometry have been predicted. Flow visualization within an annulus, and correlations for the heat transfer have been presented. Simulation of transient thermal convection within a horizontal enclosure holding two layers and flow over a range of Rayleigh and Prandtl numbers in enclosures have been measured. The influence of annular ribs and other protrusions within a cylinder on convection have been studied. Convection in spherical annuli, and the stability, influence of Prandtl number, and transients of flow occurring in a sphere have been described.

Porous media

Much of the work on buoyancy-driven convection in porous media is covered in section DP. Studies cited in the present section [112F–115F] include three-dimensional flow at a rectangular corner, transient flow in an eccentric annulus, and convection effects on thermal ignition within a porous medium.

Mixed convection

Much of the recent work on mixed convection and internal flows is cited in the present section [116F–126F]; however, some material is also described in section C on channel flows. Studies on mixed convection in vertical channels including potential flow reversal and instabilities and turbulent mixed flows between vertical parallel plates or in annuli have been described. Other studies include fully developed convection in a horizontal channel heated from below, measurements of convection in a partial enclosure, and optical measurement of the velocity distribution in mixed convection in a horizontal layer. Mixed convection in enclosures with local heat sources and with various types of ribs and other obstacles, as well as in a packed bed, have been described.

Miscellaneous studies

A number of other enclosure geometries and flow conditions for buoyancy-induced convection have been considered [127F–158F]. These include the influence of vibration and variable gravity conditions as well as the potential for injection into the flow. Special geometries include the region between two side-by-side cylindrical rollers, localized heating in enclosures with large variations in properties, the influence of sharp corners, and convection from vertical and horizontal extensions to enclosures. Unsteady convection in prisms and convection in wedge-shaped cavities and square partition cavities have been considered. The effect of partitions and dividers, the influence of very low Prandtl number, and buoyancy driven convection in loops have been reported. Variable thermophysical properties can have a significant influence on convective flows. The influence of polar fluids and the possibility of a thermal quadrupole have been reported. Convection in systems undergoing phase change, either melting or solidification, can have a significant influence on the rate and uniformity of the phase change. Application of hydrodynamic and Reynolds analogies to buoyancy-driven convection have been explored.

Applications

A number of convection problems relate to specific applications as well as being of a general nature in improving our understanding of fundamental problems in flow and heat transfer. Some of these applied works have been described this year [159F–172F]. Some consider the heat transfer in cooling down or heating up enclosed vessels, others consider energy storage systems or convection in mercury lamps, cryogenic systems, nuclear fuel canisters, and the canning industry. Still others consider convection in solar collectors, television receivers, and in electronic packaging.

NATURAL CONVECTION—EXTERNAL FLOWS

Natural convection in external flows continues to be a topic of extensive research. There are both fundamental and applied studies for various geometries. Theoretical analyses and experimental measurements have been reported for many problems. There is a growing interest in the effect of turbulence on natural convection. Two common geometrical configurations are vertical surfaces and horizontal surfaces. Other geometries have also been considered.

Vertical surfaces

Natural convection on vertical surfaces such as plates, rods, cylinders, etc. has been studied experimentally and/or theoretically [1FF–39FF]. These papers report work on both steady and unsteady flows; the stability of natural convection boundary layers is also considered. In some studies, the conjugate heat transfer with natural convection is analyzed. Natural convection with surface roughness and in porous media is investigated. Research has also been extended to non-Newtonian fluids, viscoelastic fluids, and micropolar fluids.

Horizontal surfaces

The unsteadiness and stability become more prominent in natural convection on horizontal surfaces heated from below. Studies of natural convection from horizontal plates, cylinders, and rings have been reported [40FF–54FF]. In some cases the effect of magnetic fields is considered. The investigations include: Bénard convection cells, micropolar and power-law fluids, porous materials, and turbulence.

Buoyant plumes

Rising buoyant plumes above a heated horizontal wire or other objects have been studied [55FF–61FF]. Both free plumes and wall plumes have been considered. In some investigations, the swaying motion of a plume is observed, while some others perform a linear stability analysis of the buoyant plume. Plume rise in stratified surroundings is of considerable interest. An algebraic stress turbulence model has been used for the prediction of buoyant plumes.

Turbulence

Whereas many studies are still focused on laminar natural convection, investigations of turbulent convection are beginning to appear. Detailed experimental measurements and computational predictions of turbulent natural convection have been reported [62FF–69FF]. The k–ε turbulence model is used for the prediction in many cases. Some modifications to the model are suggested to take account of the non-isotropy. The Reynolds stress model and the heat flux transport equation have been used to predict turbulent natural convection. One paper reports an evaluation of several turbulence models with reference to experimental data.

Other studies

Natural convection heat transfer in more complex geometries and thermal boundary conditions is considered [70FF–86FF]. The geometrical complexity is caused by fins and fin arrays. Convection from a porous and/or rotating sphere is studied. Instability in convective flows is also a topic of interest. One study pertains to the cooling of a moving sheet by natural convection. An interesting investigation determines the optimum hair diameter for minimum natural convection from a hairy surface. Similarly, the convection from a periodically stretching surface is considered.

CONVECTION FROM ROTATING SURFACES

As in recent years, a few studies were reported in the literature concerning convection with rotating boundaries.

Rotating disks

Several investigations dealt with heat transfer to or from rotating disks, either single disks or co-rotating disks, and cones. For these geometries, theoretical analyses were reported on boundary layer stability [2G], turbulent convection between co-rotating disks (as in data storage disk drives) [3G], films on disk surfaces [4G, 6G], sinusoidal-shaped disks [5G], concentrated heat sources [9G], and non-Newtonian fluids [10G, 11G]. Experiments with co-rotating disks examined transient free convection in induction motors [1G], explored flow oscillations [7G], and illustrated thermal characteristics of data storage disk drives [8G].

Rotating channels

Analyses were presented for forced flow convection in rectangular channels rotating about axes perpendicular [12G] and parallel [13G] to the channel axis. Experiments were performed [14G, 15G] to explore flow and heat transfer in radial channels.

Other flows with rotating surfaces

Four studies [17G, 18G, 20G, 21G] dealt with natural convective effects in planar layers rotating about an axis perpendicular to the plane. Stability of a radially heated circular Couette flow [16G] and in a rotating porous annular layer [22G] were explored. The use of modulated rotation rate was investigated [19G] for promoting growth of monocrystals in a vertical cylindrical crucible.

COMBINED HEAT AND MASS TRANSFER

Papers reviewed in the present category cover a number of somewhat disparate areas such as convective heat transfer on surfaces through which mass flows can occur (e.g. a porous surface), blowing and suction flows, film cooling, heat transfer with jet impingement, drying systems, and a number of miscellaneous heat and mass transfer studies.

Transpiration

Transpiration [1H–6H] includes flows and heat transfer in which there is a mass flow through a permeable or porous surface. When the flow is positive into the region where the main convective flow, occurs it is generally called injected flow; when the fluid is drawn from the mainstream flow through the surface, one generally says suction occurs. Studies done in the past year include those for flow over a wedge with uniform suction or injection, a two parameter integral method for laminar transpired boundary layer flows, transpiration of a non-Newtonian power-law fluid or a micropolar fluid, and transpiring flows with injection or suction with both buoyant and forced flows.

Film cooling

With film cooling, a fluid (usually a gas) is introduced at one or more discrete locations on a surface over which a high-temperature fluid flows. The injected fluid effectively lowers the temperature in the boundary layer and thus decreases the heat transfer to the wall surface. Recently there have been a number of studies on film cooling [7H–19H] in high temperature gas turbines, though the technique is also used for protection of rocket nozzles and other high temperature applications. Studies simulating cooling of a turbine blade include experiments on convective heat transfer with one or two rows of injection holes, the influence of the endwall on the heat transfer to a film-cooled blade, and the use of leading edge film cooling as well as full coverage film cooling where a large number of injection holes are used on a surface of a blade. Other studies include the use of a film-cooled circular cylinder to simulate the flow and heat transfer process in the leading edge region of a turbine blade and numerical schemes for predicting the film cooling performance on a blade. Sometimes flat surfaces are used for convenience to study important parameters that influence film cooling performance in both experiments and numerical predictions. These studies include the influence of density ratio both on heat transfer and hydrodynamics, the importance of swirl on film cooling, the influence of an embedded vortex and the inclination of a surface to the main flow on film cooling, and the influence of the number of holes in full coverage film cooling.

Heat transfer to jets

Jets occur in many engineering systems; in particular, impinging jets are widely used to obtain high local heat transfer rates on both flat and curved surfaces. In many cases the fluid in the jet is the same as that of the ambient; such submerged jets may be gas or liquid. Other impinging jets contain fluid which is different from that of the surroundings or may contain liquid or solid particles. These fluids may have a significantly greater heat capacity and thus have a very different heat transfer. One of the heat transfer problems is the spreading and interaction of jets with the free-stream or with other neighboring jets.

Recent studies [20H–37H] have considered the influences of entrainment from the surrounding fluid and of temperature-dependent fluid properties including the use of carbon dioxide near its critical point, as well as development of turbulence models for analyzing heat transfer and the use of a non-uniform velocity profile. Studies of heat transfer on curved surfaces include experiments and analysis of heat transfer from impinging jets to concave surfaces. The use of multislot jets to cool a moving permeable surface, two-dimensional jets for controlling temperatures in micro electronic systems, and impingement heat transfer that would occur internally to a turbine blade, have been studied. The characteristics of an offset impinging jet, the mixing and turbulent transport in round jets, and heated jets in a crossflow and in supersonic coaxial reacting jets have been reported. Turbulent structure and heat transfer for a two-dimensional impinging jet of gas–solid suspensions have been reported.

Drying

A large number of papers [38H–62H] are concerned with drying processes. Here, there is a close link between the heat and mass transfer processes. Studies include those for drying of granular beds, evaporation from liquid droppings and coatings, and thermal stresses induced during drying.

Other papers report on drying of grains using convection air systems, microwave devices, and even superheated steam. Solar drying has been reported for the drying of a variety of fruit and seeds, at times combined with convective cooling. Other applications of air and superheated steam for drying systems have been reported for the drying of paper, tobacco, timber, coal, and several agricultural products.

CHANGE OF PHASE—BOILING

In recent years thermal transport phenomena associated with liquid-to-vapor phase change have emerged as primary areas for research, modeling/simulation, and system development. The archival heat transfer literature in 1990 reflects substantial activity in: film and droplet evaporation, boiling incipience, pool and flow boiling—including nucleate and film boiling, as well as enhancement techniques, and fluid mechanics of two-phase flow. One hundred and seventy-nine papers dealing with ebullient and evaporative heat transfer are surveyed in this section. The reader may also find reference to these phenomena in the papers dealing with Change of Phase—Condensation (JJ), Heat Transfer Applications—Heat Pipes and Heat Exchangers (Q), and Heat Transfer Applications—General (S).

Film and droplet evaporation

The heat transfer rates and temperature fields associated with evaporation, from thin liquid films and small drops, are of importance in refrigeration equipment, liquid fuel combustion, the control of airborne pollutants, and in a variety of thermal control techniques. Moreover, a clear understanding of thin film evaporation is fundamental to the development of mechanistic relations for boiling heat transfer.

The effect of an inert gas on external evaporating layers of water and ethanol [24J], the transient evaporation of a cryoliquid [27J], and a liquid exposed to a high velocity laminar gas stream [23J] is reported. Reference [6J] explores the influence of the mass fraction of inert gas on two-phase flow in a horizontal tube. The behavior of evaporating two-component liquid films was studied numerically in ref. [2J] and experimentally in ref. [26J].

Radial flows of thin, evaporating films were examined numerically in ref. [13J], and in ref. [22J] for both a stationary and rotating disk. The empirical study reported in ref. [9J] also addressed this geometry. The dynamics and stability of ultrathin liquid films, controlled by long-range molecular forces, and the literature in this field, were the subject of the 1987 Max Jakob Memorial Award lecture by S. G. Bankoff [1J].

The thermal performance of evaporator tubes attracted considerable research interest. While ref. [8J] reported the effect of non-uniform heating, refs. [16J, 10J, 3J] documented the enhancement effects of microfins, rib-roughness, and a spirally-coiled tube on the evaporation rates and pressure drops in evaporator tubes. Reference [18J] discussed the optimal design of an integrated evaporation system, including consideration of capital-energy cost trade-offs. Correlations for falling film heat transfer coefficients along horizontal pipes are given in ref. [12J].

The evaporation of droplets in a hot gas is of particular importance to the analysis and prediction of liquid fuel combustion. Reference [5J] focuses on the unsteady evaporation of a single droplet, while refs. [7J, 14J] examine the thermofluid interaction between neighboring fuel droplets undergoing evaporation. An experimental study of the thin film evaporation of gasoline was reported in ref. [21J].

Droplet evaporation was also the subject of ref. [15J], which examined the effect of a monolayer coating, and of ref. [19J], which theoretically explored the effect of dissolved solids on the properties of a liquid spray. The evaporation of liquid drops in an immiscible liquid, as encountered in direct-contact heat exchangers, was studied analytically in ref. [4J] and experimentally in ref. [17J].

Spray cooling was addressed in ref. [20J], which deals with a second-law analysis of this thermal control technique, ref. [25J], which experimentally investigated its application to continuous casting, and ref. [11J] which focused on the effects of surface wettability.

Boiling incipience and bubble characteristics

Nucleation and boiling incipience mark an abrupt transition in the thermofluid behavior of liquids and are of special importance in the design of phase-change systems. References [42J–44J] explore the anomalous boiling incipience behavior of highly-wetting dielectric liquids on metallic and ceramic surfaces. Homogeneous nucleation in binary mixtures and during rapid depressurization is examined in ref. [39J] and ref. [33J], respectively, and ref. [28J] studies the effect of non-condensables on vapor explosions. The stability of nucleate boiling is addressed in ref. [36J], while the growth rate of vapor bubbles on a variety of surfaces is the subject of refs. [30J, 35J, 37J].

The 1990 archival literature provides insight into bubble–bubble interactions in a stagnant liquid [41J], in turbulent flows [29J], in boiling on horizontal tubes [32J], and in bubble streams [34J]. Studies of bubble nuclei formation [38J] and Marangoni convection on gas bubbles [40J], as well as the development of a mathematical description of a bubbly liquid [31J], are also reported.

Pool boiling

The continuing need to refine the understanding of thermal transport in nucleate pool boiling has stimulated several new modeling studies [46J, 76J, 96J] and experimental efforts to measure fundamental boiling parameters, including the wetted fraction of the surface [65J], the extent of the metastable region [109J], the contribution of wall conduction [75J], and the thickness of the two-phase layer [70J]. The heat transfer characteristics of refrigerants boiling on cylinders and tubes [47J, 58J, 59J], as well as the the boiling behavior of electrolytic solutions [64J], helium [68J], and hydrogen [69J] also received attention.

A large number of studies was devoted to determining the thermal transport rates in nucleate pool boiling for specific geometries. These included: a stationary sphere [55J], a free-falling sphere [110J], the evaporator section of a closed thermosiphon [81J, 83J, 84J], grooves covered with plates [50J], surfaces with cylindrical capillaries [74J], composite structures of insulators and conductors [56J], horizontal tubes [53J], shell-and-tube evaporators [54J], tube bundles [52J], face seals [106J], and microelectronic chips [77J]. The 1990 archival literature also provides evidence of renewed interest in the acoustics of boiling fluids [79J, 80J, 99J] and the influence of microgravity [108J] and high gravity [105J] on nucleate pool boiling.

Determination of the peak nucleate boiling heat flux, or the so-called 'critical' heat flux (CHF), is of crucial importance in the design of steam generators and phase-change thermal management systems. Reference [72J] examines the critical heat flux in bottom-sealed, vertical channels. Reference [57J] explores the effect of step changes in joule heating on the critical heat flux on a wire and ref. [100J] deals with this transition under low pressure. Reference [90J] describes the numerical results obtained with a conduction/evaporation model of critical heat flux.

Film pool boiling attracted considerable interest in 1990, with much of the effort focused on experimental studies of film boiling heat transfer in various geometries, including horizontal surfaces [91J], vertical surfaces [60J, 61J], inclined plates [82J], horizontal cylinders [49J, 93J, 94J, 101J], and spheres [48J, 97J, 102J]. The influence of surface conditions on film boiling is explored in ref. [67J], via the effect of a surface coating, and in ref. [97J], via the use of oxidized and roughened surfaces. The transition from nucleate boiling to film boiling in liquid nitrogen is studied in refs. [87J, 88J]. A review of data and correlations for the Leidenfrost point, or minimum heat flux in this mode, is given in ref. [71J].

The enhancement of pool boiling, in both the nucleate and film boiling modes, continued to occupy many investigators in 1990. The boiling of R-113 from a structured surface is described in ref. [45J] and the effect of a surfactant on the pool boiling of both a pure liquid and a binary mixture is examined in ref. [104J]. Pool boiling heat transfer from porous surfaces is reported in refs. [63J, 73J, 95J, 107J], from a sphere embedded in a porous medium in refs. [89J, 103J], and the stability of boiling in porous media in ref. [92J]. The boiling of pure liquids and binary mixtures in the presence of an applied electric field is described in refs. [51J, 66J, 85J, 86J, 98J]. The influence of ultrasonic fields on pool boiling is reported in refs. [62J, 78J].

Flow boiling

Boiling in the presence of a circulating fluid is profoundly affected by the mass fraction and distribution of the vapor phase, or the prevailing flow regime, and is sensitive to geometry and orientation. A survey of the 1990 archival literature reveals a series of publications dealing with fundamental experimental studies of: the incipience of flow boiling in horizontal channels [151J, 152J], subcooled flow boiling of refrigerants [127J, 157J] and binary mixtures [156J] in vertical channels, saturated flow boiling of refrigerants in horizontal tubes [134J], potassium vapor generation in coiled tubes [111J], and saturated flow boiling of water in vertical channels [125J].

A general correlation of saturated flow boiling [129J] and a comprehensive theoretical treatment of forced convection boiling [150J], along with mechanistic studies of subcooled flow nucleate boiling [160J], inception of flashing in reactor channels [139J, 149J], the effects of pressure waves on boiling along fuel elements [153J], and annular flow at high evaporation rates [146J] are also described in the literature. Improvements in flow boiling heat transfer were reported in ref. [154J]—for helically-coiled tubes, in ref. [136J]—for twisted-tape tubes, and in ref. [143J]—for offset strip fins. The quenching of hot surfaces by high mass flow rates of water is examined in ref. [115J], the effects of magnetic fields on boiling water in ref. [126J], and an experimental/numerical study of the boiling of sodium, in a pin bundle geometry, is the subject of ref. [117J].

Critical heat flux for subcooled flow boiling in round tubes continued to attract significant attention in 1990, as reflected by the publication of refs. [118J, 120J, 131J–133J, 138J]. Additional studies examined CHF in other geometries, including helical coils [114J], horizontal and inclined tubes [124J], annuli [116J, 137J], rod bundles [113J], and parallel channels [135J]. The enhancement of the critical heat flux through artificial roughness in vapor generating channels was described in ref. [159J] and the effects of pins, studs and micrgrooves on CHF for simulated microelectronic chips in ref. [145J].

The mechanisms and prediction of 'burnout' for impinging submerged liquid jets are discussed in refs. [130J, 142J] and for the mist-annular flow regime in tubes in refs. [140J, 144J]. Analytical studies of critical heat flux addressed stratification in horizontal tubes [162J], asymmetrically heated channels [141J], and the velocity slip ratio between the phases in annular flow [123J]. The relevant numerical studies focused on CHF during power transients [148J] and the development of a comprehensive model based on a film-dryout criterion [158J].

Empirical studies of post-CHF behavior in flow boiling examined periodic surface re-wetting [112J, 121J], variations in the thickness of the vapor film [119J], the effects of liquid 'flooding' rate [147J], and the film boiling behavior of a sphere [122J]. Analytical modeling efforts, during this period, dealt with turbulent film boiling from a non-isothermal surface [155J], development of a closed set of equations for film boiling in channels [128J], and an assessment of various proposed models [161J].

Fluid mechanics of flow boiling

Thermal transport in boiling two-phase flow is intimately related to the fluid mechanics of the flowing mixture and much insight can be obtained from data on the prevailing flow regime, void fraction, and pressure drop in a pipe or channel. The 1990 literature extends the use of flow regime maps to the refilling of hot horizontal tubes [163J] and compares flow regime predictions and experimental results for two-phase flow loops in microgravity [177J]. Observations are reported on the behavior of the wake behind a cylinder in cross-flow [167J], liquid film thickness in a vertical channel [175J], and void fraction variations in subcooled flow boiling [179J]. Several empirical studies explored the influence of specific enhancement techniques on flow parameters, notably [176J] for tubes with helical ribs and [178J] for imposed low frequency fluctuations in liquid feed flow. Boiling-induced instabilities in two-phase flow occuring in steam generating channels [174J] and liquid nitrogen evaporators [164J, 165J], as well as wall temperature fluctuations in vertical tubes [171J], also received attention. Fundamental two-phase flow modeling issues were addressed in refs. [166J, 169J], the modeling of flashing flow in an inclined pipe in ref. [172J], choked non-flashing flow in ref. [173J], analytical determination of density-wave instabilities in ref. [168J], and the calculation of pressure drop in long boiler tubes in ref. [170J].

CHANGE OF PHASE—CONDENSATION

Research on condensation in 1990 included investigating the effects of: contouring the surfaces for efficient condensate removal; varying the surface material; changing the global geometry; changing orientation or varying the thermal boundary conditions; and rotating the condensing surface. There also were studies of variable property effects and of special transient behavior. Forms of condensate included films, droplets (including nucleating droplets) and collapsing bubbles. A review of the recent Japanese literature was presented in one paper [1JJ].

Surface effects [2JJ–18JJ]

Numerous papers investigated the effects of fins, grooves, and similar surface features designed for enhanced condensate removal. Experimental evaluation of geometries as well as techniques for analysis were reviewed. Several papers demonstrated the effects of changing the wall material and using polymers and non-ferrous and ferrous metal surfaces. *In situ* measurements to assess fouling effects were also presented.

Geometry and boundary condition effects [19JJ–31JJ]

Effects of geometry including bundle depth, reflux density and orientation were investigated. One paper showed significantly higher heat transfer coefficients when a horizontal tube was non-circular. Several authors investigated the effects of surface rotation using a drum, a cylinder (with scraper) or a cone. Several entries showed the effects of non-uniform thermal boundary conditions and of the external region being a packed bed.

Analysis techniques [32JJ–38JJ]

Papers in this category stressed the analytical techniques. Topics ranged from computing the effects of gas flow on film condensation to computing, with kinetics theory, molecular behavior during phase change.

Free surface condensation [39JJ–43JJ]

Papers which investigate the growth of droplets included effects of being in residence within a gas mixture. The study in one paper allowed droplet coalescence. A photographic analysis of a condensing bubble showed the dynamic unsteady change in geometry throughout the collapse. A similar study described the collapse of a vapor jet emerging into a subcooled pool of liquid containing absorbed gas.

Noncondensable gas effects [44JJ–48JJ]

Analyses were presented for computing the film condensation of vapor from a gas stream. Experimental results were presented for condensation of droplets in a gas stream and for film condensation on a grooved tube in the presence of air. The thermal resistance of an air layer in stratified, horizontal, concurrent flow was evaluated by one research group.

Transient effects including nucleation [49JJ–56JJ]

Transient condensation of steam on a large metal block in the presence of air was measured, as was the film condensation on the endwall of a shock-tube. The dynamics of bubble condensing events were experimentally investigated under the condition where the injection rate gives a dilute system of bubbles. The dynamics of condensation in a two-pipe condenser were documented and a transient technique using LASER heating was employed for measurement of surface evaporation heat transfer coefficients. An analysis based upon material and heat balances was proposed for describing the generation of liquid phase in a vapor–gas medium. Heterogeneous nucleation of water droplets in a boundary layer was analytically described. The reversibility of condensation and the associated hysteresis loop of the condensation curve were discussed.

Binary mixtures and property effects [57JJ–62JJ]

Analytical solutions for film condensation of a refrigerant mixture and for general binary mixtures were presented. Property variation effects were demonstrated by use of a laminar film condensation model. The effects of surface tension on film condensation in a porous medium were analyzed, leading to dimensionless parameter groups. A correlation which included property variation and turbulence effects for condensation on a shear-free interface was presented.

CHANGE OF PHASE—FREEZING AND MELTING

Phase change problems—namely, freezing and melting—are reviewed in this section. Experimental, theoretical, and numerical investigations have been attempted and the various subcategories encompass Stefan problems; solidification of alloys/metals and casting processes; crystal growth; issues related to frost, ice, snow, and soils; applications relevant to freezing/melting; influence of convection; continuous casting and other processes; numerical simulations and approximation methods; experimental papers; directional solidification problems; storage problems; and miscellaneous applications.

Stefan problems

Papers involving the Stefan problem appear in refs. [1JM, 2JM]. In particular, in contrast to the traditional classical heat conduction Stefan problem, these papers deal with the notion of a hyperbolic Stefan problem.

Solidification of alloys/metals and casting processes

Papers appearing in this subcategory encompass solidification in the formation of ingots and castings [5JM, 6JM], investigations of temperature distributions and cooling rates [7JM], and solidification of alloys cooled from the top [3JM, 4JM].

Solidification issues involving crystal growth

Numerous papers appeared last year dealing with various issues in solidification in crystals. These appear in refs. [8JM–43JM]. Since it is beyond the scope of this review to overview specific issues, readers are strongly encouraged to look at references outlined.

Applications involving freezing and melting in frost, ice, snow, and soils

Research papers involving solidification issues in this subcategory appear in refs. [44JM–51JM]. Much of the research has focused on thermal characteristics during solidification including location of freezing fronts.

Freezing and melting: applications

Relevant applications involving freezing and melting encountered in solidification processes involving phase change appear in refs. [52JM–59JM].

Convection and/or flow effects

The influence of convection in phase change problems is an important consideration. Analytical/experimental and related simulations involving convection appear in refs. [60JM–72JM].

Continuous casting and other processes

The related papers appearing in this subcategory include analytic solution of liquidus position for application to continuous casting of steel [73JM], simulation of strip casting process by twin roll method [75JM], simulation for progress of solid–liquid coexisting zone during continuous casting of carbon steels [76JM], and columnar and equiaxed dendrite growth in continuously cast products [74JM].

Numerical simulations and approximate methods

This subcategory continues to be an active research area and numerous papers dealing with numerical simulations and new and/or approximate methods of development appear in literature. These papers are identified in refs. [77JM–92JM].

Experimental investigations

Papers specifically addressing certain important considerations and dealing with experimental investigations in phase change problems appear in refs. [93JM–101JM]

Directional solidification issues

Papers dealing with directional solidification issues during phase change are specifically outlined in this subcategory. These include refs. [102JM–107JM].

Energy conversion/storage problems

Applications relevant to energy conversion and storage included an electrical storage heater using the phase change method of heat storage [109JM], thermal performance of a heat storage module employing PCMs with different melting temperature [110JM], heat transfer model for thermal energy storage [112JM], thermal storage in aquifiers and energy recovery for space heating and cooling [108JM], digital control of a heat recovery and storage system [114JM], thermal heat transfer enhancements in an energy storage unit [113JM], and numerical simulation for latent heat storage [111JM].

Miscellaneous problems and applications

Numerous other related problems and various applications addressing phase change (freezing and melting) appear in refs. [115JM–143JM].

RADIATION IN PARTICIPATING MEDIA AND SURFACE RADIATION

Participating media studies

The papers in this section [1K–15K] consider radiative transfer in one-dimensional participating media, semi- or near-infinite media, and new/improved solution methods for solving the radiative transfer equation. Five models for planar layers are given, investigating the effects of reflective and diffuse boundary conditions, inhomogeneity and variable properties, anisotropic scattering, and the presence of sources and sinks. Several transient analyses are given, along with an analysis of propagation from a point source through a scattering layer. Similar discussions of radiative transfer in half-space, near-infinite, spherical, and cylindrical geometries are given in several other papers. A variety of methods are used to solve radiative transfer problems in porous media, packed beds, and fluidized beds, including integral equations and approximations therein, finite difference methods, flux techniques, and discrete ordinates methods. Methods for calculating view factors pertinent to some of these systems are included under the Surface Radiation category.

Multi-dimensional radiative transfer

New and/or improved solution methods for two- and three-dimensional geometries are grouped in this category [16K–32K]. Once again, rectangular enclosures received a great deal of attention, but there are also several papers which discuss spherical and cylindrical geometries. Numerical results with anisotropic scattering are computed from integral formulations and discrete ordinates methods and compared to simpler techniques employing differential approximations and scaling solution algorithms. Transient solutions for isotropically scattering media by direct integration are also analyzed. Finite volume and finite difference methods similar to numerical techniques used in computational fluid dynamics and convective heat transfer applications are also employed. A new superposition technique for isotropically scattering media is also discussed. Three-dimensional solutions concentrated on the development of zonal and network models to reduce required computation times, and test results for simple cases were often given. Applications ranged from duct and channel flows in high temperature/combustion systems to solar receivers. Again, papers on view factors are included under the Surface Radiation heading.

Radiation combined with conduction

Nine papers grouped into this category [33K–41K] included several applications-oriented solutions involving window systems, laminated materials, packed beds, and rectangular liquid droplet radiators. Several other papers analyzed one-dimensional planar and spherical geometries filled with absorbing, emitting, conducting, and anisotropically scattering media. In all cases, numerical results were given, and a variety of methods similar to those described in the preceding sections were utilized. Examples include finite element, finite difference, zonal models, and the Galerkin method. A method based on the use of quasi-Green's functions to convert boundary value problems into equivalent integral equations was also described. In several of the window applications, experimental results were obtained for comparison.

Radiation combined with convection

Radiation coupled with convection is studied in these papers [42K–56K]. A variety of configurations are considered, including two-dimensional studies of Poiseuille flow, rectangular channel flows, boundary layers along horizontal and vertical plates, turbulent and compressible flowfields, and particle-laden flows. Solution techniques include a modified zonal, S–N discrete ordinates, spherical harmonics, finite element, finite difference and product integration. In addition, several papers discuss inverse solution methods. Some experimental results are given for comparison, but the emphasis of most of the papers is numerical. One-dimensional treatments of particle-laden liquid films and porous media with transpiration are also given.

Radiation in combustion systems and high speed reacting flows

Twenty papers [57K–76K] deal with flame propagation, heat transfer, reactions and particle fields in combustion systems, radiation from combustion products, and supersonic flows. Topics covered include ignition, flame propagation, thermophoresis, interactions with turbulence, reaction rates and non-equilibrium conditions, and spectral distributions. Systems ranged from basic laboratory combustion studies to industrial furnaces and internal combustion engine systems to supersonic and hypersonic flight regimes. Most of the models were one-dimensional, but a few used zonal models to incorporate two- and three-dimensional effects.

Surface radiation

If one excludes atmospheric radiation, almost all real engineering systems where radiative transport plays a significant role involve interactions with surfaces; therefore, this heading may seem somewhat vague. Of the papers included here [77K–89K], five deal with view factors pertinent to both single- and multi-dimensional calculations. The remaining papers deal with radiative transfer from thin films, reflectance and scattering properties of land, and the emissivity of missile noses and cryogenic surfaces. Note that the categories above and below contain solutions for problems with various surface boundary conditions.

Laser radiation

A growing area of research describes interactions between materials and relatively high power laser beams [90K–97K]. Most of the papers in this section deal with heat treatment, welding and/or cutting processes, and damage thresholds in metals or semiconductors. Other papers had more unique applications, ranging from X-ray generation and nuclear fusion from shocked foils to modeling of the radiative transport in a chemically reacting atomic iodine laser amplifier.

Radiative transfer in gases

Atmospheric radiative transfer and radiative properties of gases are considered here [98K–103K]. Several models of radiative transfer in the atmosphere covering a wide range in complexity are described and compared to experimental data. Papers presenting the radiative properties of SO_2 and CO_2 are included here, while papers on the radiative properties of combustion gases were included in the combustion system section.

Radiative properties—solids and liquids

This section is composed of papers giving engineering data on reflectance, transmittance, emissivity, photoluminescence, and absorption in solids and liquids [104K–119K]. Materials discussed include plastic composites, glasses, refractories (including one review article), metals, semiconductors, crystals, and soil. Many of the papers deal with high temperature properties and appropriate experimental measurement techniques.

Scattering

The papers in this section [120K–131K] consider scattering by particles in systems where radiative transport is important. The first subgroup of papers use Mie and/or Rayleigh theories to obtain scattering coefficients for high temperatures and polydisperse distributions. Roughness effects are considered for large coal particles. A second group of papers examines angular scattering patterns from fibers, considering the effects of fiber orientation and/or finite length. A third group of papers examines the effects of constructive/destructive interference of coherent radiation propagating through multiply-scattering, Rayleigh regime media. Finally, backscattering from a sphere to an emitting planar surface is analyzed via a Monte-Carlo calculation.

Experimental techniques

While many of the papers in previous sections include experimental results, the objective of papers in this section is to describe new experimental techniques not necessarily linked to any specific application. A small group of papers fall into this category [132K–138K]. Topics considered include an absolute spectral irradiance scale, a standard for specular reflectance measurements near normal incidence in the 2.5–25 μm region, holographic optical elements for the far IR, a variable reflectivity surface, several emissivity measuring devices, and the photothermal technique for measuring gas temperature/species concentration fields.

Miscellaneous

Only two papers did not fit well into any of the previous categories [139K, 140K]: one deals with combined heat and mass transfer effects on the size distribution of water aerosols, and the other deals with the thermodynamic efficiency of the conversion of diluted radiation into work.

NUMERICAL METHODS

The area of numerical methods continues to receive significant attention. Numerical methods are actively being developed and applied to a wide variety of problems. In this review, the papers that focus on the application of a numerical method to a specific problem are included in the category appropriate to that application. The papers that deal with the details of a numerical method are reviewed in this section.

Heat conduction (direct problems)

Since the solution of heat conduction represents the fundamental task in any numerical method, new techniques are often tested on heat conduction problems. Also, the solution of a number of heat conduction situations is of interest in many practical applications. Direct heat conduction problems have been analyzed by the methods described in refs. [1N–17N]. Both finite element and finite difference methods have been developed. Three-dimensional problems are increasingly given attention. The efficiency and accuracy of the solution are improved by the use of adaptive meshes and better iterative techniques. Problems with heat sources and with large variations of thermal conductivity are considered.

Heat conduction (inverse problems)

In recent years, considerable research has been done on the solution of inverse problems in heat conduction. In such problems, some information about the solution is available and the task is to obtain the specification of the problem, such as the boundary conditions. The papers on inverse problems deal with diverse topics including contact thermal resistance, stability, accuracy, and ill-conditioned system of equations [18N–23N].

Phase change

When freezing or melting occurs, the heat conduction problems involve an additional feature, namely the tracking of the interface. Some methods directly find the location of the interface, while others use the enthalpy method, which indirectly determines where the interface lies. Grids that expand or contract with the movement of the interface are suitable for simple situations. Problems with complex interface geometries are usually solved on a fixed grid. Crystal growing is an important area for the application of a phase-change numerical method. These topics have been investigated in refs. [24N–34N].

Convection and diffusion

The differential equations for momentum, energy, or concentration contain the convection and diffusion terms. A satisfactory formulation of these terms valid for all flow rates is crucial to the success of a numerical method. Therefore, considerable effort is spent on the development of new and improved convection–diffusion schemes. The papers dealing with this topic present adaptive-grid techniques, improvements on the conventional upwind and central-difference methods, and strategies for avoiding unphysical wiggles in the solutions [35N–51N]. Representative schemes have been tested on a group of model problems.

Solution of flow equations

Calculation of convective heat transfer usually requires the solution of the associated flow field. Numerous papers describe the development and testing of numerical methods for the solution of the flow equations [52N–74N]. Implementations of the methods on personal computers and on supercomputers with parallel processing have been discussed. The solution methods include direct solvers, multigrid techniques, and collocation. Body-fitted and adaptive grids are often employed. A number of papers report formulations with non-staggered grids. Free-surface flows and open boundary conditions are also discussed.

Turbulent flow

Special numerical considerations required for the computation of turbulent flow are described in refs. [75N–79N]. The issues that are discussed include: convergent techniques for the two-equation model, multiple time scales, buoyancy driven flows, wall functions, and two-phase situations.

Other studies

Techniques and computations employing embedded grids, combustion, crystal growing in magnetic fields, and cooling of electronic circuits are reported in refs. [80N–86N].

TRANSPORT PROPERTIES

This year papers on transport properties are categorized by type of substance. Papers dealing strictly with thermodynamic not transport properties are excluded.

Homogeneous solids

New methods were described for estimating spatially varying thermal conductivity and thermal diffusivity by solving the inverse heat conduction problem based on transient temperature measurements [2P, 10P, 13P]. A number of other experimental and analytical techniques for measuring thermal transport properties in homogeneous solids were described [3P, 6P, 9P, 11P, 14P, 16P, 17P, 19P].

Several papers were concerned with thermal transport properties in superconducting materials [5P, 8P, 15P]. New measurements of thermal transport properties were also reported for the following materials: rubbers [4P], gallium garnets [18P], single crystal 1-alanine [12P], the glass system 77% B_2O_3–23% PbO doped with ZnO [1P], and the $LaNi_5H_2$ system [20P]. The thermal properties of adobe were discussed in the context of its use as a thermal regulating material [7P].

Heterogeneous materials

The effective thermal conductivity of heterogeneous materials was an active area of investigation. Theoretical methods were presented for predicting the effective conductivity of dispersed or porous media [28P, 35P, 42P]. The effective conductivity of cellular materials was the subject of two theoretical works [22P, 36P]. Experimental studies were reported of the effective thermal transport properties of various systems: materials made from pressed powders [31P, 32P, 39P]; composite stone and brick building materials [41P]; modified polymeric coatings with filler [40P]; glass-reinforced plastic [23P]; polycrystalline CdS, CdSe and CdTe [21P]; porous MR material [24P]; and a variety of dispersed materials using the periodic heating method [46P]. Two works were concerned with multilayer systems [25P, 30P].

The transport properties of fibrous media are receiving increasing attention. A three-part work was presented on carbon–carbon fiber composites, including both measurements and mathematical modeling [43P–45P]. Other theoretical studies concerned with predicting effective conductivity in fiber systems included refs. [26P, 29P, 33P, 34P]. Measurements were reported of thermal transport in a variety of mostly fiber-based ceramic materials for application in high temperature reactors [37P].

Two works considered the thermal transport properties of an important but theoretically difficult class of materials: foams [38P] and aerogels [27P].

Liquids

Several papers considered thermal transport properties of molten material. Transport properties of molten salts were studied theoretically [54P] and experimentally [50P]. The laser flash method was used to measure thermal diffusivity in boron oxide melts [49P]. Two works reported measurements of thermal conductivity in molten polymers [51P, 52P].

Several works focused on experimental techniques for measuring thermal conductivity [47P, 48P] and viscosity [53P, 55P] in liquids.

Gases, plasmas, and fluids generally

Experimental data on diffusion coefficients were used to estimate thermal conductivities of N_2O and CO_2 [58P]. A model kinetic equation for a non-ideal gas was solved to derive transport coefficients [62P]. A model was considered for a multi-species, multi-speed lattice gas to simulate thermal and chemical transport [63P]. Kinetic theory was used to calculate thermal conductivity and viscosity of lithium and sodium vapor in the interval 800–2000 K [60P]. Measurements were reported on the viscosity of gaseous mixtures of Freon-14 and helium [61P].

Reviews were presented on experimental methods for determining thermophysical properties of fluids [67P] and on thermophysical properties near the critical point [59P]. A method was described for calculating the thermal conductivity of dense mixtures using a revised Enskog theory [57P]. Measurements were reported on the thermal conductivity of steam at pressures up to 30 MPa and temperatures up to 700°C [65P, 66P]. A four-parameter equation of state was used to estimate thermodynamic and transport properties of non-polar fluids [68P].

Two theoretical studies reported transport coefficients of air plasmas [56P, 69P]. Plasma kinetic transport theory was extended beyond the weak turbulence limit [64P].

HEAT TRANSFER APPLICATIONS—HEAT EXCHANGERS AND HEAT PIPES

Activity centers upon the continued exploration of the fundamentals of heat pipe operation and their design and performance. A number of heat exchanger designs and operational features are taken up and the findings reported.

Tube bundles

Research on heat transfer in tube bundles includes a number of analytical studies and correlations. Noteworthy are papers which consider the influence of twisted tubes and coiled tubes on heat transfer [2Q, 3Q]. Other studies treat multi-passage tube performance, transversely finned tube correlations, radiant pipes, platen tube bundles, and a new heat transfer correlation and flow regime map for bundles [11Q, 8Q, 7Q, 9Q, 6Q]. Experimental investigations focus on the influence of turbulent intensity on heat transfer and pressure drop, forced and combined convection with water, and the influence of non-uniform heat transfer on tube performance. Two studies deal with liquid metal heat transfer [1Q, 13Q].

Fins and various shapes

A number of papers examine the enhancement of heat transfer by the use of such devices as twisted flow, fins of wire and spirals, helical baffles, and helically coiled tubes [32Q, 27Q, 25Q, 30Q]. Other studies consider modeling natural convection and radiation from arrays of vertical, rectangular fins, condensing flow in a porous bed, coefficients in finned-stirred tank systems, an industrial fin-tube economizer, and the performance of a pin-fin array [23Q, 34Q, 22Q, 28Q, 14Q]. Steam generators using helium in steeply bent coils, a cooling system using desiccant matrices and the performance of the cross finned tube exchanger in angled air flow are also considered [20Q, 26Q, 38Q]. Yet other considerations are examined: the influence of materials used in tubes and fins, frost formation effects, spray-wetting of a finned tube bank, and the effect of flow-disrupting rings [18Q, 15Q, 16Q, 19Q, 35Q]. Specific applications of finned tubes lead to a number of reports: copper finned tubes in gas-fired water heaters, evaporative tubes, water chillers, hollow fin heat exchangers for He II, louvered fins, and rotary dryers [21Q, 29Q, 37Q, 36Q, 31Q, 33Q, 24Q]. A review of augmentation techniques for heat transfer surfaces concludes this subsection [17Q].

Heat exchangers

Design of heat exchangers and off-design behavior is the theme of a number of studies [88Q, 94Q, 112Q, 120Q, 142Q]. The modeling of heat exchanges is approached from a number of viewpoints: penetration theory, modular theory, simultaneous optimization, quasidynamic, and others [39Q, 96Q, 138Q, 51Q, 95Q]. The performance and optimization of these devices is estimated by a second law attempt to attach a quality to the energy exchange process [119Q]. Other papers consider plate exchangers, optimization of wet-surface exchangers, influence of exchanger effectiveness on vapor absorption devices, complex assemblies of exchangers, and enhanced heat flow by oscillation [132Q, 98Q, 82Q, 79Q, 53Q, 68Q, 54Q, 86Q, 87Q].

Rather specific considerations are the focus of a significant number of investigations, e.g. use of polymers in heat exchangers, the effects of vitreous-enamel coating, the experimental performance of a rectangular, two-phase natural circulation loop, perforated plate heat-exchanger analysis, stirred tank reactor heat transfer, RODbaffle exchanger technology and the liquid-droplet radiator [48Q, 55Q, 60Q, 61Q, 67Q, 74Q, 97Q, 106Q–111Q, 141Q].

Considering heat exchanges from particular areas of application yields a diverse group: heat flow in arterial tubes [44Q, 49Q], heat exchange in boilers, fluidized-beds and furnaces [45Q, 50Q, 52Q, 65Q, 69Q–71Q, 85Q, 118Q, 121Q, 140Q], compact heat exchangers [59Q, 99Q, 104Q, 130Q, 133Q, 134Q], and condensers [43Q, 83Q, 136Q]. Convectors, particularly as applied in heat pump service, are the subject of study as well as other specialized cooler and heater devices [42Q, 63Q, 92Q, 101Q, 122Q, 128Q]. Other heat exchanger studies are reported for separator-reheaters, air heaters, water heaters, incineration of contaminated air, and refrigerant evaporation [102Q, 93Q, 46Q, 129Q, 103Q, 62Q]. Network synthesis and optimization models and strategies have attracted considerable interest involving different approaches not only for conceptualizing new systems, but determining the optimal retrofit of existing systems [40Q, 56Q–58Q, 64Q, 72Q, 73Q, 80Q, 84Q, 105Q, 135Q, 139Q]. Research in regenerators spans a spectrum from design and analysis to very specific applications, e.g. gas turbines and closed cycle MHD power systems. Also treated are the influences of bed packing, thermal conditions on coolant properties [47Q, 81Q, 89Q–91Q, 100Q, 114Q, 116Q, 124Q, 125Q]. Heat-pump exchangers are examined for performance in spacecraft application and ground-source installation [41Q, 117Q, 131Q]. Rotary heat exchangers and dryers are modeled mathematically, and studied for a number of uses [113Q, 115Q, 126Q, 127Q, 137Q]. Scraped surface exchangers are modeled for laminar and vortical flow [75Q–78Q]. Eutectic storage mediums and long cooling spray ponds complete this subsection [123Q, 66Q].

Heat pipes

Analytical and experimental efforts combine to significantly extend our knowledge of the underlying principles of operation, design, and performance of this device. Analyses consider start-up, two-phase binary systems, mass and energy transport through wick and pipe wall, transient modeling, and standardized design procedures [158Q, 165Q, 149Q, 157Q, 162Q, 170Q, 173Q, 148Q]. Experimental results pertain to a number of conditions: gravity assisted devices, throughflow designs, magnetic fluids, thermal-hydraulic effects and the testing (and modeling) of a micro heat pipe [176Q, 175Q, 154Q, 164Q, 144Q]. Two-phase units are considered for performance limits and local heat transfer; single and two-component, liquid metal systems are tested for operating characteristics [172Q, 146Q, 155Q, 159Q, 167Q, 177Q]. Wick parameters and heat-pipe response to thermal exposure are examined. Additional papers consider solar energy transport, energy storage performance and use in a waste-heat recuperator. Yet others deal with production and construction features. Noteworthy is the attempt to fabricate capillary heat-pipes by cathodic-deposition [143Q, 145Q, 147Q, 151Q–153Q, 160Q, 161Q, 168Q, 169Q]. A collection of papers describes the status of the heat-pipe in industrial practice and research activity in various countries [150Q, 156Q, 163Q, 166Q, 171Q, 174Q].

Transient operations

Various influences which bear on the transient response of heat exchanges are described: finite wall capacitance, non-steady flow, non-stationary temperature fields, non-steady mixing, and varying conditions in vapor generating channels [180Q, 187Q, 183Q, 188Q, 179Q, 178Q]. Other studies report on the dynamic simulation of plate heat exchangers and the use of the Coanda effect to pulse flow for heat transfer gain [181Q, 186Q]. For testing heat exchangers the single-blow test is assessed, a non-contact, IR system has been developed and tested, and a sensor developed for heat-pipe control [182Q, 192Q, 193Q]. The link between condensation pressure pulses and exchanger vibration is examined [184Q]. For specific systems the flow and heat transfer in Stirling engine regenerators and the simulation in a grain dryer are reported [189Q–191Q, 185Q].

Fouling

Unlike other years only a few papers are concerned about the effect of exchanger fouling upon performance [194Q–196Q].

HEAT TRANSFER APPLICATIONS—GENERAL

Papers in this section are arranged in sub-sections according to the application in which heat transfer is involved.

Manufacturing, processing [1S–38S]

The largest effort (about 1/3) of the applied research in this subsection went into manufacturing processes, and about 1/3 of that was experimental. The temperature field was studied in cutting [16S, 37S] and grinding [7S, 30S] as was energy transfer in drilling [34S]. Heat transfer in rolling [17S, 23S, 29S], melting and solidifying [14S, 32S] and thermal regimes in casting [1S] were established. Heat flow, heat generation, and beam deflection are reported for welding processes [6S, 20S, 35S, 36S]. Two papers cover vapor deposition [9S] and melt spinning [3S]. Quenching [2S] and spray cooling [33S] are discussed as well as surface hardening [13S]. Heat transfer is involved in extrusion [31S] and pultrusion [4S].

Modeling analysis is applied to the sinter cooler [19S], the crystallizer [27S, 28S] and the production of molten glass fibers [8S]. Experiments establish heat transfer in mixers [10S, 24S] and an analysis treats Ohmic heating of food [11S]. Computation optimizes packaging [21S] and describes formation of cracks by thermal stresses [26S] in computers. Heat transfer in pipe fittings [18S] and valves [15S] was determined. Protection of structures by polymer coatings swelling when heated is described [25S]. Asymptotic analogies for heat and mass transfer are reviewed [22S].

Buildings, ground [39S–53S]

Insulation is studied in walls with respect to location [49S], retrofitting [39S], thermal bridges [43S], and in windows [53S]. Calculation of air currents [51S] and comfort conditions [44S, 48S] are discussed. Heat transfer and flow was calculated and measured in finned tubes and thermosyphons [47S, 50S].

Several papers consider thermal conditions in the ground: foundations and underground spaces [52S], thawing by sprinklers [41S], wellbores [40S], and disintegration of rocks [45S].

Refrigeration, cryoengineering [54S–58S]

A review discusses frost formation [56S]. Experiments study chilling of meat [54S] and the melting of ice [55S]. The heat flow into cryogenic vessels is examined [57S].

Boilers, reactors [59S–64S]

Heat and mass transfer was reported in chemical reactors [61S, 62S] and in rotating vessels [59S]. The effect of heat transfer was also studied in staged combustion [60S], for devolatilization [63S], and for ignition of solid fuel particles [64S].

Electronics [65S–79S]

The thermal performance of conduction-cooling for chips is studied experimentally and analytically [69S, 73S, 76S]. The state of the art of the thermal management of electronic packages, and wiring boards is reviewed [72S, 74S, 77S]. Numerical modeling and control of multicomponent systems is discussed [66S, 70S] as is their optimization [71S]. Microwave and infrared heating of films was analyzed [67S, 75S]. Attention was given to flow and heat transfer in electric machines and transformers [65S, 68S].

Bioengineering [80S–84S]

Heat transfer to tissue is predicted [80S] as well as the temperature distribution under normal conditions [83S], tumor conditions [82S], and optical irradiation [84S]. Thermal burns caused by warm water circulation are also considered [81S].

Nuclear energy [85S–88S]

Convective and conductive heat transfer was analyzed in a fast reactor [86S], and in a fluidized bed reactor [85S]. Heat transfer was also studied in a model shutoff valve [88S].

Gas turbines [89S–95S]

Cooling of turbine blades was studied by liquid vaporization [93S], by molten metal [90S], and using low molecular weight fluids for space applications [89S]. Radiative heat transfer to vanes is analyzed [91S] and the thermal conductivity of thermal barrier coatings is measured [95S]. Pyrometry for turbine blades is discussed [94S], and proper boundary conditions are identified for computer analysis [92S].

Piston engines [96S–98S]

Numerical analyses describe the instantaneous heat flux at the cylinder head [98S] and the aluminum piston [97S] as well as the fluid flow and transient heat transfer [96S] in Diesel engines.

Aeronautics, astronautics [99S–108S]

The temperature field in thermally protective ablative materials is calculated [102S] and the current status of heat transfer knowledge in composite materials and solid–solid interfaces is discussed [99S]. An active thermal insulation of semi-transparent porous medium with gas injection protecting it from radiation heating is considered [103S] and computer analyses of current and future hypersonic vehicles are discussed [100S]. Analysis and experiment are combined to determine non-steady heat transfer on scale models [108S]. Aerothermal prediction for slender blunted cones is compared with experiments [106S] and a Monte-Carlo method is used to study hypersonic flow for a broad range of Knudsen numbers [101S]. Formulae are proposed to calculate radiative heat transfer to blunt bodies with destructive coatings in hypersonic flow [105S]. A 3-D code is designed to calculate hydrodynamics and magnetohydrodynamics of a stellar atmosphere [104S].

SOLAR ENERGY

Solar radiation

The design of solar energy systems requires accurate predictive models of the solar insolation on a collecting surface as a function of geographic location, time of year and time of day, from both direct and diffuse radiation. A considerable number of papers dealt with this subject. Several models of the directional distribution of diffuse sky radiance were reviewed [14T]. A critical review was presented of water vapor absorption coefficients in the 8–13 μm spectral region [9T, 10T]. Other works included models of synthetic hourly radiation [8T], modified Ångstrom-type models [1T, 18T], a method for using Fourier series to estimate radiation transmitted through glazings [5T], a model for determining seasonal total extraterrestrial radiation [17T], a method for using global radiation measurements to infer the spectral radiation distribution on a horizontal surface [6T], a study of the latitude dependence of the monthly average daily diffuse radiation [15T], and an investigation of ground-reflected radiation and albedo [11T]. Two studies were concerned with solar radiation on inclined surfaces [7T, 12T].

Direct solar radiation is often modeled by considering the sun to approximate a black body at $\sim$5800 K. However, a thermodynamic analysis which treated the sun as a thermal reservoir for driving a Carnot engine, accounting for atmospheric processes, yielded an effective sun temperature of 3600 K for clear sky and about 2000 K for a highly turbid sky [13T].

Studies of solar radiation in specific locations have a particular utility. One such study developed an empirical formula for hourly solar radiation over Bahrain, which has 11 h of average daily sunshine [2T]. The availability of wind and solar energy in Qatar was evaluated [3T]. An anisotropic, diffuse-sky insolation model was used to determine the optimum inclination of solar collectors during the cooling season in China [16T]. Another study utilized data taken by the Viking spacecraft to calculate a detailed set of solar radiation data for the surface of Mars [4T]. This may prove useful for future solar energy systems on that planet.

Large central systems

Data processing techniques for evaluating receiver steady-state efficiency were studied and applied to the Solar Thermal Central Receiver Pilot Plant near Barstow, California, and the International Energy Agency/Small Solar Power System Central Receiver Power System near Almeria, Spain [20T]. A parametric study was reported of the 50 kW dish Stirling system in Riyadh, Saudi Arabia [21T]. A method was developed for determining the thermal loss from a solar central receiver at normal operating conditions [19T].

Collectors, concentrators, receivers

Several authors reported numerical modeling of flat plate solar collectors [31T–34T, 38T]. Test results were reported of an extended-surface flat plate collector [36T], and an automated procedure was devised for testing collectors using the ANSI/ASHRAE 93-1986 Standard [29T]. Evacuated collector tubes were studied [24T, 37T]. Numerical studies were conducted of a porous-medium solar collector [30T] and of phase change heat transfer in a flat plate collector [39T]. A non-linear dynamic regulator was developed for a paraboloidal collector [35T]. Inflatable concentrators for solar propulsion were described [27T]. These are intended as a heat source for a hydrogen engine aboard the Solar Rocket. Three papers discussed cavity solar receivers [23T, 25T, 28T], and two studies of heat pipe receivers were reported [22T, 26T].

Applications

Domestic water heating by solar energy was the subject of several papers [40T, 43T, 50T, 54T]. Various studies considered the application of solar energy to air heating [52T], agricultural drying [41T, 47T], desalination [56T], floor heating with hot water [57T], to drive chemical reactors [42T, 46T] and stills [55T], as part of an HVAC system [49T], and as a heat source for a Brayton engine, as part of the NASA Space Station Freedom [51T]. Solar energy as the heat source for different types of refrigeration and cooling cycles was considered [44T, 45T, 48T, 53T].

Passive solar, thermal storage, and miscellaneous

Passive solar heating was modeled by several authors [59T, 60T, 74T]. A detailed study of thermal mass in commercial buildings was undertaken [58T]. A single-tube integrated collector storage system was described [69T]. Thermal stratification in hot storage tanks was studied experimentally [65T]. An Interzone Temperature Profile Estimation technique was described for modeling of heat transfer in earth-sheltered buildings [66T]. Solar ponds received considerable attention [62T–64T, 67T, 72T, 73T]. A Model Reference Adaptive Control system was developed and tested [70T]. Theoretical studies were conducted on the effects of infrared absorbing gases on window heat transfer [68T] and of solar radiation induced natural convection in enclosures with conducting walls [61T]. Economic as well as technical aspects of solar space heating in Turkey were discussed [71T].

PLASMA HEAT TRANSFER AND MHD

Modeling for plasma characterization

One major emphasis in the characterization of thermal plasmas has been the development of formalisms for describing non-equilibrium effects. Typical approaches use a two-fluid model for electrons and heavy particles, combined with some rate kinetics model for energy transfer [1U, 2U, 10U, 13U, 15U]. Heavy particle–electron non-equilibrium in an atmospheric pressure argon rf discharge is described [13U] as a function of excitation frequency, with the heavy particle temperature decreasing and the difference between heavy particle and electron temperatures increasing as the rf frequency is increased from 3 to 40 MHz. The increasing degree of non-equilibrium for decreasing pressure is described [15U]. Non-equilibrium plasma properties are used in this reference as they were published in ref. [14U]. A model for the rf plasma generator is described in ref. [3U] in which all equations are consistently two-dimensional, but LTE is assumed. Multi-component mixtures in rf reactors have been modeled [8U, 17U, 18U], combining the rf discharge calculations using Maxwell's equations, the conservation equations, and determination of the chemical composition using thermodynamics or reaction kinetics, to describe the dissociation of $SiCl_4$ [18U], or the composition of an argon–oxygen and argon–hydrogen mixture [8U]. A more general description of the influence of diffusion on the chemical energetics in inhomogeneous processing plasmas is discussed [9U]. Non-equilibrium characteristics in dc plasma jets have been calculated [1U, 2U] for low pressure Ar jets and turbulent jets using the two-fluid approach and describing ionization using kinetics, and in ref. [10U] where the Ar ground state population is included separately from the excited states in the reaction kinetics. An equilibrium calculation of a similar jet is reported in refs. [4U–6U] with the calculation domain including the arc region within the nozzle and looking at the jet mixing with the cold surrounding air. In ref. [11U], the turbulent Navier–Stokes equations are solved together with the energy equation and Maxwell's equations and a chemical kinetics description to model the decomposition of $SiCl_4$ in a hybrid dc and rf reactor. Excitation non-equilibrium descriptions based on collisional-radiative models are presented for a pulsed plasma [7U] and for a wall-stabilized arc [16U]. Expressions for the electrical conductivity and the thermodynamic properties of a non-ideal plasma are derived [12U].

Modeling of plasma–solid interaction

The non-equilibrium region in front of the wall is described by dividing the boundary layer into a continuum region and a free fall region [20U]. The importance of thermo-diffusion and diffusion thermo-effect when electrons are present is shown [33U] for the specific application of space vehicle reentry, and the importance of ion–electron recombination energy to the heat transfer at reduced pressures has been demonstrated [32U] for the case of plasma sintering. Further descriptions of plasma–wall interactions include a surface energy balance for the anode surface of an MPD arc thruster [34U] for predicting anode erosion, the influence of the evaporation of Cu from the anode on the arc characteristics (no major ones found) [37U], the evaporation of nozzle material in nozzle flow arcs and the resulting nozzle clogging as applicable to circuit breakers [22U], and the interaction of the material evaporated from a cathode spot with the background gas [21U, 31U]. Reference [25U] describes a zero-dimensional code for plasma wall interaction with ablation, and the model of the melting of an ingot due to arc heating using a finite volume method is described in ref. [24U]. A model of the influence of the cathode shape on the convective heat transfer in welding arcs is presented in ref. [36U], and the mixing of reactants injected into a plasma channel flow is modeled in ref. [29U]. The radiative exchange between a plasma and surrounding furnace walls is given in ref. [30U].

Description of plasma particle heat transfer including rarefaction effects are given in ref. [28U] where an analogy to electrostatic probe theory is used, while in ref. [27U] an analogy with radiative heat transfer in a high pressure sodium lamp is used. In ref. [23U], a model is presented for the heat transfer to a particle in a non-equilibrium plasma and enhanced heating due to higher transport of ionization energy is found. A gas kinetic approach for the modeling of heat and momentum transfer to a particle is given in ref. [19U]. Reference [35U] describes the momentum and heat transfer to particles in plasma jets using an empirical distribution for the temperatures. The effect of quenching in the plasma synthesis of ultrafine particles is modeled by assuming condensation on nuclei as the growth mechanism [26U], and controlled cooling is recommended for obtaining control over particle properties.

Diagnostics

The radiation source strength of Ar has been measured in a rf plasma [51U] and consideration of non-equilibrium effects has improved the data at lower temperatures. The optical transmission in noble gases excited by a pulse discharge is given in ref. [41U], and the absorption of laser radiation by a metal plasma as encountered in laser welding is described in ref. [46U].

Several authors report on sophisticated diagnostics experiments to characterize film deposition processes. Reference [40U] reports simultaneous measurements of particle velocity, size and temperature in a plasma spray jet, using a two color laser beam. A focused beam is used for LDA measurements, while a wide beam is used for scattering measurements. Two color pyrometry is used for particle temperature determination. In another plasma spray characterization experiment [49U], the particle temperature in the moment of impact on the substrate surface is measured pyrometrically by focusing two sensors from different angles on a selected spot on the surface and looking for signal coincidence. Characterization of a plasma jet using laser diagnostics is also reported in ref. [44U], where the electron density is determined using coherent Thomson scattering, and the plasma velocity by measuring the Doppler shift of scattered light in two different propagation directions.

Reference [47U] describes the results of a microwave thermal plasma vapor deposition experiment of a diamond film using emission spectroscopy for determining C_2 species densities, and mass spectroscopy for hydrocarbon radicals; the dominant species have been found to be CH_4 and C_2H_2. Deposition species from an anodic vacuum arc plasma are reported in ref. [43U], using mass spectroscopy with energy analysis and Langmuir probes for determination of the charge. In another vacuum arc experiment [45U], LIF is used for determination of the dominant species, however, it has been found that a rapid reduction of the arc current and electron density has been necessary to reduce collisional quenching. Further vacuum arc characterization has been carried out by measurement of electron and ion energies [39U] and by characterizing cathode spot instabilities using streak photography [50U]. An Ar plasma generated by rf induction in a pressure range from 2.5 to 580 Torr has been investigated using a combination of emission spectroscopy, LIF, and absorption spectroscopy, and a kinetics model describing the electron–atom interactions, resulting in density distributions and electron temperatures [55U]. An enthalpy probe in an Ar–He rf plasma has been used to verify a two-dimensional model [56U]. Two papers report on the improvement of Langmuir probe measurements, giving a numerical correction for the edge effect in small probes [42U], and describing a concentric double probe arrangement for measurements in turbulent plasmas [53U].

New measurement techniques are reported in ref. [54U] describing a magnetic probe imbedded in the electrode material for measurement of the current distribution of a moving arc attachment, in ref. [52U] using acoustic velocity measurements to determine densities in low density plasmas, and in ref. [38U], where absorption of soft X-rays for plasma density measurements is used. A high resolution, three-dimensional time of flight mass spectrometer has been developed for probing space plasmas [48U].

Specific applications

Plasma deposition attracted a large number of publications, for example in special editions of journals such as the *IEEE Transaction on Plasma Science*. Several review articles are included on vacuum arc coatings [65U], on arc spraying [67U] and on plasma spraying [63U], and mass, momentum and energy transfer effects are described. Thermal plasma CVD has attracted considerable interest with the development of high rate diamond deposition processes, with efforts concentrating on the plasma characterization at the edge of the non-equilibrium boundary layer [59U, 66U]. Models of the heat and mass transfer in a hot filament reactor point toward the importance of thermal diffusion effects [58U]. Expansion of a microwave assisted combustion plasma has led to the formation of diamond particles [60U], and the supersonic expansion of methane resulted in the deposition of amorphous carbon films [62U].

Systematic studies of energy transfer processes in transferred arc plasmas are reported in refs. [61U, 64U]. Mixing of a hot plasma jet with surrounding cold gas is described based on measurement of average gas temperature measurements [57U], and the effects of electrode surface contamination on the arc motion is given in ref. [68U].

MHD

Several authors calculated fluid flow and heat transfer for various geometries and conditions, such as flow in an annular channel with a non-uniform magnetic field [79U], in a rectangular cavity with a transverse magnetic field [70U], and through a rotating permeable disk through which the fluid is sucked from the boundary layer [71U]. The convection effects in a conducting fluid exposed to a transverse magnetic field near a leading edge are calculated in ref. [73U], and the effects of the magnetic field on the heat transfer and friction in the stagnation region of a sphere are given in refs. [75U, 76U]. Similarly strong effects on drag and heat transfer coefficient are found due to the Hall current [77U]. An analysis of the heat exchange between unmixed magnetic and non-magnetic fluids is given in ref. [69U]. New solution methods are given for MHD flow in a horizontal channel with free convection [78U], and for arbitrary geometries using a hodograph transformation of the streamfunction [72U]. A stability analysis for predicting the boundary layer breakdown is presented in ref. [74U], and the effect of the temperature dependence of the transport properties in the Poiseuille flow is calculated in ref. [81U]. Experimental data are presented in ref. [80U] for a vertical tube flow of a two-phase mixture of NaK and nitrogen with a transverse field leading to asymmetric heat fluxes.

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HEAT TRANSFER APPLICATIONS—HEAT PIPES AND HEAT EXCHANGERS

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