Pergamon

Int. J. Heat Mass Transfer. Vol. 40, No. 16, pp. 3729–3804, 1997

Printed in Great Britain
0017–9310/97 $17.00+0.00

PII: S0017–9310(97)00003–3

Heat transfer—a review of 1994 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 1994. It is intended to encompass the English language literature, including English translations of foreign language papers and also includes some foreign language papers for which English abstracts are available. Although the literature search was inclusive, the large number of publications made selection in some of the review sections necessary.

Several conferences during 1994 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 International Solar Energy Conference "*Solar Engineering* 1994" was held on March 27–30 in San Francisco, California, sponsored by ASME, JSME and JSEE. The *40th International Instrumentation Symposium* at Baltimore, Maryland on May 1–5 was connected with a display and demonstration of instruments for temperature, pressure and flow measurement and their application. It was sponsored by the Instrument Society of America. The *4th InterSociety Conference on Thermal Phenomena in Electronic Systems* was held in Washington, D.C. on May 4–7. Proceedings are available at the IEEE Service Center, 445 Hoes Lane, Priscataway, NJ 08854. The *International Conference on New Trends in Nuclear Systems* at Pisa, Italy on May 30–June 2 was devoted to water cooled reactors, presenting the state-of-the-art and discussing future research needs. It was sponsored by the University of Pisa.

The 39th ASME International Gas Turbine and Aeroengine Congress "*Turbo Expo* 94" at the Hague, Netherlands on June 13–16, presented among others, papers on film cooling and unsteady heat transfer. A Darryl E. Metzger Memorial Session honored an outstanding contributor to gas turbine development. Ernst R. G. Eckert received the 1994 IGTI Aircraft Engine Technology Award. The *6th AIAA/ASME Thermophysics and Heat Transfer Conference* at Colorado Springs held on June 20–23 dealt with topics like rotating disk, film, impingement transpiration cooling, effects of turbulence and transition. The *25th Plasmadynamics and Lasers Conference* was held in Colorado Springs on June 20–23. The 1994 Annual Conference of the American Solar Energy Society "*Solar* 1994", at San Jose, California on June 25–30 discussed progress in the solar energy field.

The secretariat of the International Center of Heat and Mass Transfer was moved to Turkey (Professor Dr Faruk Arinç, Mechanical Engineering Department, Middle East Technical University, Ankara 06531, Turkey) because of the war in Yugoslavia. It organized an *International Symposium on Heat and Mass Transfer under Plasma Conditions* on July 4–8 at Cesme, Ismir, Turkey to present the state-of-the-art for scientists and engineers in the field of plasma transport phenomena, fundamentals and applications.

The highlight of the conferences in heat and mass transfer is the *International Heat Transfer Conference* organized every fourth year by the Assembly for International Heat Transfer Conferences. The 10th conference was held at Brighton, UK on August 14–18. The sessions each day contained poster session reviews, poster sessions, keynote lectures and discussions. Industrial sessions and special keynote lectures were also provided, as well as open forums and film and video sessions. Topics of the sessions were: numerical techniques and modeling, external forced convection, heat transfer in nuclear and conventional systems, condensation and direct contact gas–liquid heat transfer, freezing, melting and solidification, internal forced convection, heat exchangers, pool boiling, particulates, porous media, natural and mixed convection, heat transfer augmentation, two-phase film with and without phase change, conduction and insulation, natural convection, applied heat transfer, flow boiling. The proceedings of the conference are contained in seven volumes and published by Hemisphere Publishing Corporation. Short courses on various topics were also arranged during the conference.

The third international conference *Heat Transfer* 94, held August 22–24 in Southampton, UK was devoted to advanced computational methods in heat

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transfer. It was organized by the Wesson Institute of Technology, Southampton, UK. The International Center of Heat and Mass Transfer held a *Symposium on Heat and Mass Transfer in Chemical Process Industry Accidents* on September 15–16 at the University of Rome.

The Winter Annual Meeting of ASME "*ME* '94" was held on November 6–11 in Chicago, Illinois. The Heat Transfer division organized its presentations in 20 sessions, panel discussions, symposia and poster sessions covering all phases of heat transfer, research and applications.

The 1993 Max Jakob Award was presented to Benjamin Gebhart in recognition of his distinguished research contributions in the areas of natural convection heat and mass transfer, stability and transition in buoyancy-induced flows, radiative transport in enclosures and environmental transport phenomena, and for leadership in the education of young engineers and scientists as a teacher, mentor and author of texts and monographs. The 1994 Heat Transfer Memorial Awards went to Adrian Bejan and Kenneth R. Diller. Avram Bar-Cohen received the Edwin F. Church Medal.

CONDUCTION

Heat transfer due to conduction is reviewed in this category to include a variety of issues. These issues are subcategorized as those dealing with contact conduction/contact resistance; layered, composite or anisotropic media; thermal waves and laser or pulse heating situations: conduction aspects associated with fins, tubes and general solids; mathematical and/or analytic models, analysis techniques and simulations; experimental and/or comparative studies; thermomechanical problems and induced stresses; inverse problems and analysis/design studies; conduction influenced by convection of flow effects; solidification and change of phase; heat conduction and microelectronics; materials processing and special applications.

Contact conduction and contact resistance

In this subcategory, a variety of issues have been dealt with during this year. [1A] discuss issues as related to the enhancement of thermal contact conductance in metallic coatings, [2A] describe the impact of a thermal boundary resistance on laser inclusion damage and [3A] include contact conductance between cladding/pressure tubes in thermal reactors. Including a comparison with experiment, a review of elastic and plastic contact conductance models are conducted by [4A].

Layered, composite and/with anisotropic media

A variety of applications have been presented in this subcategory including: thermal, mechanical and rheological evolution during processing of multilayer thermosetting composites [5A], macroscopic modeling and thermal transfer in composites with interfacial thermal barrier [6A], thermo-elastic related problems [7A, 8A, 9A, 10A], dealing with transverse thermal conductance in the cure of thermosetting composites [11A], multi-layered soils [12A], effective thermal conductivity of a two-component composite [13A], heat conduction issues with application to a sandwiched plate and stringers [14A], and requirements for laminates which will exhibit zero bending curvature under steady-state heat transfer conditions [15A].

Thermal waves, laser/pulse heating

Heat waves resulting from hyperbolicity of the heat conduction equation is described for a two-dimensional problem by [16A], in conjunction with coupled thermoelasticity with nonlinear materials properties by [18A] and by [22A] on their significance in heat conduction. Applications dealing with laser/pulse heating and transients included thermal response of an enclosure to periodic excitation [17A], molecular dynamics of heat conduction in solid materials [19A], overheated metastable states in pulsed laser deposition vs laser radiation wavelength by [20A] and the effect of an elliptical Gaussian laser beam in the generation of ultrasonic waves in water [21A].

Conduction in fins, tubes and solids

Relatively fewer papers appeared in this subcategory. The effects of heat conduction in a semi-finite solid with an exponential-type initial condition and influenced by an instantaneous laser source is described by [23A]. Other aspects of conduction heat transfer in annual finds of various shapes [24A], effective thermal conductivity influence in multi-dimensional bodies [25A], fins with temperature dependent surface heat flux [26A] and diffusive transport across a wavy plate composed of annular sectors [27A], have been conducted. Optimization related problems are discussed by [28A, 29A] for fins and spines.

Mathematical models, analysis techniques and simulations

As in previous years, this subcategory continues to receive widespread research attention. Issues range from developing improved mathematical models, to the improvement and/or new analytical and/or numerical techniques and numerical simulations to help provide an understanding of the physics of the problem. Since it is almost impractical to identify specific issues of each contribution appearing in this subcategory, only a gist of the relevant efforts are summarized here. Analytical and heat transfer-associated physically based models including the use of integral transforms, symbolic mathematics, kernels and the like appear for various applications to heat conduction by [30A, 31A, 35A, 36A, 37A, 38A, 39A, 40A, 43A, 46A]. Those associated with numerical analysis, modeling and simulations encompass computational analysis with applications to resistance spot welding of a pre-coated steel sheet [32A], calculations on the effects of grain sizes and orientations on the thermal conductivities of composites [33A], moving boundary in a composite medium [34A], the effects of global conductivity in repetitive structures [41A], and miscellaneous applications [42A, 45A, 47A]. A discussion of the generalized Fourier law of heat conduction is given by [44A].

Experimental and/or comparative studies

Experimental and numerical studies encompass unsteady non-periodic heat transfer due to temperature perturbations [48A], laser-assisted chemical vapor deposition of copper [50A], thermal contact resistance across bolted joints [52A], and [53A] discuss heat generation at low temperatures inside coal piles. Other experimental studies include dynamics of cutting tool temperatures [49A], thermal modelization and experiments on the dependence of current flow in superconducting microbridges on light [51A].

Thermal/thermal–mechanical problems

The effects due to temperature and temperature distributions in structures and materials play an important role in the estimation of the induced stresses. The studies which appeared this year can be broadly categorized as thermo-mechanical problems influenced by conditions involving contact, friction and the like and those in which these effects are neglected as in simplifications in which residual induced stresses due to temperature are predicted. The former involving modeling wear at intermittently slipping high speed interfaces [57A], thermo-mechanical frictional contact based on complementarity relations [58A], fully coupled behavior around a rigid cylindrical heat source buried in clay [59A], models for anti-friction spindle bearings of high-speed machine tools [60A], thermal effects due to surface films in sliding contact [61A], factual theory for elastic contact and heat transfer analysis [62A], temperature maps for pin-on-disk dry sliding [63A], effects of temperature and elasticity and pressure build-up in linear pad bearings [64A], and sliding bodies with wear and heat generation [65A] appear in this subcategory. The latter include applications to residual stresses in polycrystalline diamond compacts [54A], thermal-stress analysis in the SIRUS-P reactor [55A], active vibration control of a flexible cantilever beam due to thermal bending moment [56A], and thermally induced stresses and displacements in a two-dimensional convective half-space with a moving heat source [66A].

Inverse problems, analysis and design studies

[67A] describes an inverse design application of super-elliptic cooling passages in coated turbine blade airfoils. Boundary element solutions of steady-state singular, inverse heat transfer equation is described by [68A]. A control theory method for solutions of inverse transient heat conduction problems is described by [69A].

Conduction/convection, flow effects

As applied to spherical and cylindrical shape models of food products subjected to hydrocooling, the transient temperatures are studied by [70A]. The influence of oscillations in thermocapillary convection in a square cavity are addressed by [71A]. Other applications include convective currents induced by periodic time-dependent vertical density gradients [72A].

Solidification, change of phase, crystals

In this subcategory appear applications describing the effects of wall heat conduction and interface thermal resistance on the phase change problem [73A], solidification of molten metal droplets impinging on a cold surface [74A], prediction of snowmelt infiltration into frozen soils [75A], similarity solution of Stefan problem [76A], and electron and thermal transport in InAs single-crystal, free-standing wires [77A].

Microelectronic heat transfer

Applications in this subcategory include effects of substrate conductivity [78A] stability of cable-in-conduit internally cooled superconductors [79A] and effects of concentric cylinders [80A] as applied to microelectronic heat transfer components.

Materials processing

Relatively few papers addressing materials processing and relevant issues appeared in the literature. The topics covered include thermal analysis of creep-feed grinding [81A], heat transfer parameters in thermosetting materials [82A], the reflective heat transfer coefficient as a function of temperature and pressure [83A], and heat and mass transfer during chilling of beef carcass [84A].

Miscellaneous studies

A variety of interesting applications all involving heat conduction are studied in the remainder of the references in this subcategory [85A–115A].

BOUNDARY LAYERS AND EXTERNAL FLOWS

The papers on boundary layers and external flows during 1994 have been categorized as follows: flow influenced externally, flows with special geometric effects, compressible and high-speed flows, analysis and modeling techniques, unsteady flow effects, flows with films and interfacial effects, flows with special fluid types and property effects, measurement techniques, and flows with combustion or reaction.

External effects

Papers which focus on external effects document the influence of elevated turbulence or turbulent wakes in the approach flow [13B, 3B, 2B] and describe wind shadow effects [5B] and wind-induced entrainment

[4B]. Also, the effects of ambient pressure fields on jets and plumes [6B] and on boundary layers [8B, 10B], the effect of induced swirl on tube and nozzle flows [1B] and the effects of gravity [7B, 11B, 12B] were discussed. The latter discussed the non-uniqueness of the eventual steady state flow. Semiconductor heat pump modules were applied to shape memory metals for reducing response times for thermal cycling [9B].

Geometric effects

One study, an antithesis to this topic, shows a means of finding an optimum size of an object for heat transfer without concern for shape [23B]. Others showed effects of square ribs [14B], wire-coil inserts [28B], pin fins [17B, 26B], a cone in a stratified flow [33B], V-shaped grooves [32B], a cross-corrugation [28B], finned heat sinks [36B], and a planar rock fracture [34B]. Others investigated heat transfer from a moving rod [21B] and a spherical-cap bubble [25B]. Several dealt with jets, one an impinging jet [18B] and another a wall jet [35B]. Several pertained to flow through beds, one was a particle bed in aseptic processing [16B], another was a grape package [24B], and a third was with cylindrical packed tubes [20B]. The effects of interaction of droplets in a cloud spray were discussed [31B]. One paper discussed the convection from a cylinder in a packed bed of particles of different size and material [27B]. Finally, several papers dealt with enhancement due to geometry. One was with an upstream eddy promoter [30B], another presented several devices for chaotic mixing [19B], a third presented an enhancement method for application to adsorption cycles [22B], and the last discussed augmentation upon venting from a cavity [15B]. A review of forced convection enhancement was given in Ref. [37B].

Compressibility and high-speed flow effects

Two papers dealt with vortex flows, one with flow over a disk [40B] and another with flow within a vortex tube [38B]. Three papers discussed high speed flight; the first focused on a viscous shock at the leading edge [41B] and the other two documented swept-wing-shock-wave/boundary-layer interaction [42B, 43B]. A similar paper dealt with the external flow field of a scramjet inlet [39B] and another discussed loss mechanisms in nozzle flows [45B]. One paper discussed the application of the Reynolds stress and thermal eddy diffusivity models to supersonic flows [44B].

Analysis and modeling

Papers in this area used such techniques as transformation [55B] and superposition [57B] to solve heat transfer problems for plane walls and rigid spheres, respectively. Wedge solutions were used, with singularities identified, to determine heat transfer near contact lines in single- and two-phase flows [46B]. Temperature distributions in lakes were analytically found using the assumption of a depth-invariant temperature [56B]. The concept that heat generated near a wall is carried away primarily by the convection parallel to the wall was applied to laminar boundary layers [48B] and a description was given of the nonlinear dynamics of pulsatile stagnation flows [58B]. A line source description was used to model convective plumes over a cylinder [50B] and a macroscopic description was used to describe a stratified system [51B]. An improved turbulence model was applied to transitional boundary layers with some success [47B], a sensible heat flux probability density function was applied to model atmospheric flows [52B], and conditional sampling was applied to describe turbulent boundary layer flows [54B]. Two papers discussed the Reynolds analogy, one was a review of turbulent Prandtl number [53B] and another discussed the Reynolds analogy for chemically reacting flows [49B]. An adaptive finite element method was applied to forced and free convection problems [59B] and an isoparametric biquadratic finite element method was applied to a flat plate flow [60B]. A computer program for simulation of geothermal reservoirs was presented in Ref. [61B].

Unsteady effects

Unsteady flow studies include the impact of a drop against a surface [69B, 77B], the passing of wakes over a surface [65B, 70B, 72B, 74B], and flow along the wall of an agitated vessel [81B]. An unstable vortex, formed in a counterflow channel by heating the closed end, was described [76B] as was the instability of the flow of a large Prandtl number fluid in a vertical slot [79B]. The growth of the convective marine boundary layer in close proximity to the gulf stream was documented by aircraft and satellite measurements [80B]. Oscillatory flow studies included one with an oscillating cylinder [67B] or with any obstacle in general [68B], a cylinder in a pulsatile flow [66B], or an oscillatory boundary layer [63B]. Heat transfer from a sphere in a traveling sound wave was presented [62B] as was a study of heat transfer in a reciprocating engine flow [64B]. The effects of thermal and saline gradient instability on ice growth [71B] and on convection within an enclosure [73B] were presented. Similar to the ice growth study was one on crystal growth in an autoclave [75B]. A solution technique for modeling unsteady behavior of co-current flow of two contacting phases was presented [78B].

Films and interfacial effects

Surface interface effects were documented for polymeric membrane formation [84B], evaporating wavy fuel films [86B], desiccant films [89B], and salt layers with grid-stirred flow [82B]. Ice formation was the topic of two studies [85B, 88B]. Finally, two papers dealt with capillary and surface tension effects, one in fluid collars [87B] and another in a hollow glass ampule [83B].

Effect of fluid type or fluid properties

Papers in this topic dealt with viscoelastic fluids flowing over a plate [99B] and over a stretching sheet [96B, 91B], flows with variable fluid properties in water boundary layers [92B], and turbulent boundary layer flows with large density gradients [98B]. A computational model for transient heat transfer in superfluid He II was presented [100B] and heat transfer from a cylinder in He II was discussed [97B]. Flows carrying particles include a liquid–solid flow in a flume [94B] and particle-laden flows [93B, 90B, 95B], the last of which contained magnetic particles.

Flows with combustion and reaction

Papers in this section included one on the cooling effect of a combustor wall [102B] and one with a chemically reactive stretching sheet [101B]. A wedge flow with chemical reactions was discussed [103B] and the effect of wall catalysis on shock-boundary layer interaction was described [104B]. Shear flows with reactions include a flow with a diffusive, exothermic reaction [107B] and a laminar diffusion flame [109B]. The effect of non-equilibrium chemistry on friction and heat transfer was discussed, in light of the reference temperature method and Reynolds analogy [108B]. Finally, combustion of a droplet [106B] and of a carbon particle [105B] was analyzed.

Measurement techniques

Entries which seem to focus on measurements include one in which infrared imaging was used to document a turbulent flow over a surface [112B], one in which velocity, humidity, and temperature were measured in an atmospheric boundary layer [110B], one in which a fast-response heat flux sensor was used to document a wing/body flow [113B], one which presented an analysis of the transient effects of thick, hot-film sensors [114B], and one where a "cold finger" was used in a high-temperature liquid near a solid surface [115B]. Finally, a impulse response technique was used to estimate convective heat transfer coefficients in an enclosure [111B].

CHANNEL FLOWS

The archival literature concerning wall-bounded flows was subdivided into the following categories: straight-wall ducts; irregular geometries; duct flows dominated by entrance effects; finned and profiled ducts; ducts experiencing secondary motions caused either by curvature, rotation or imposed swirl; pulsatile or oscillatory ducted flows; two-phase flow in ducts; non-Newtonian flows; and miscellaneous duct flow.

Straight-walled ducts

Research was conducted in a variety of ducts having uniform, but arbitrary cross section. One paper [6C] was concerned with the asymmetries and inherent flow three-dimensionality established in straight-walled ducts heated from one side. Microchannel fluid flow and heat transfer will undoubtedly be examined more extensively in the years to come; this year two papers [15C, 20C] address forced convective heat transfer of liquids through microchannels. Fully developed Poiseuille flow was considered in the presence of constant wall temperature in a pipe of arbitrary cross-section [9C]; other studies of constant wall temperature included elliptic cross-sections [3C], circular-segment ducts [10C] and flows at high Rayleigh numbers [7C]. Step changes in wall temperature [2C] and heat flux [18C] examined the mixed-convective regime; conjugate heat transfer was also considered in a vertical pipe containing sodium [8C]. Exponential heating was considered together with the accompanying axial flow variations [16C]; axial temperature profiles were also studied to model uranium extraction heat [19C]. A careful examination of the existing literature on convex surface heat transfer in annular passages was undertaken using extensive data sets [5C]. Heat transfer and drag of slit flow was studied by employing a magnetic fluid on one of the channel walls [4C]; asymmetric boundary conditions were also imposed by moving one of the walls of a rectangular duct [14C]. Arrays of parallel plates having discrete heat sources [12C] as well as those with distributed heat sources [1C] were studied to optimize the cooling of electronic components; only flush mounted elements were considered in this subsection of the review (also see the subsection on finned and profiled ducts). The role of turbulent transition on heat transfer augmentation was examined [11C] as well as the effects of turbulence generated by an inlet blade wheel [13C]. Finally, the heated walls of a reactor and the associated transport to gas flows was considered [17C].

Irregular geometries

Two- and three-dimensional ducted flows are ubiquitous in practice and provide a challenging environment to both experimentalists and modelers. Perhaps the most common deviation from straight-walled ducted flows is one where periodic changes in cross-sectional area are imposed; several numerical studies considered the heat transfer characteristics in ducts of this nature [24C, 26C, 27C]. Cusped ducts were studied in a mixed natural and forced convection regime; buoyancy was shown to enhance heat transfer rates as well as the friction factor [23C]. Ducts having an S-shape, such as those found in some gas turbines, were studied together with the effect of wakes emanating from the upstream compressor blades [22C]. Taking the scale of complex geometries to extreme limits, we found research covering microgeometries such as microvalves, microrotors and microbearings [21C], as well as the convoluted passage existing in mining tunnels where the modeling of air handling is addressed [25C].

Entrance effects

Most practical flows are significantly influenced by the boundary conditions imposed by the approaching fluid. These entrance flows are indeed important and rich in detail, but do not receive the attention that the fully-developed regime attracts. One example of the complexity which can be brought to bear on a geometrically simple duct flow, is the use of one-walled injection or suction in conjunction with constant wall heat flux [30C]. The effects of water spray injection angle at the inlet of a duct on the velocity and temperature field is also considered [33C]. The influence of inlet geometry on heat transfer rates was studied in a circular duct with reentrant, square-edged, and bell-mouth inlets; uniform wall heat flux was imposed [31C]. A step change in inlet temperature in a developing channel flow was investigated [32C]. Mixed convection in the thermal entrance region of both horizontal and vertical pipes gives rise to flow reversal; numerical analysis of the heat transfer characteristics at low Peclet numbers was performed [35C]. Convective instability phenomena caused by density effects were examined in a visualization study [29C]. Transient effects were considered in developing laminar and turbulent flow caused by pressure waves [34C] and various boundary conditions including wall heat flux, solid–fluid interface temperature and thermal entrance length itself [28C].

Finned and profiled ducts

The balance between heat transfer augmentation and pressure loss is a classic problem in the thermal-fluid sciences. The literature was replete with studies examining various aspects of this problem covering the gamut from electronic cooling applications to gas turbine blade design. The largest group of papers in this subcategory would probably be best described as rib-roughened channels. The heat transfer and pressure drop in rectangular channels was studied with triangular ribs [51C], ribbed-grooved walls [65C], a rib-roughened bottom wall [46C], and for single rib, in-line multiple ribs and staggered multiple ribs [59C]; one study covered a large parametric space including Reynolds and Prandtl number effects [61C]. Similar studies were carried out in triangular ducts [64C], circular ducts [67C], and in a rotating serpentine passage [45C]. A fundamental examination of the relationship between turbulence and heat transfer augmentation was carried out in the transitional flow regime [53C]. Flows in passages encountered in gas turbine blades are complicated by secondary motion and turbulence promoters. Several studies considered the effects of turbulence enhancement [36C, 47C, 52C, 55C, 60C]; secondary flow effects can be found in the next subsection. Electronic cooling remains a "hot" area, with papers addressing electronic components on one wall of a fully developed flow [39C], laminar flow between parallel plates [49C], multi-board modules where comparisons between simulation and experiments were performed in a naturally vented chassis [40C], and convective heat transfer over the five exposed faces of a low profile electronic package [62C]. An attempt to develop a generic optimization strategy was also proposed [57C]. Passages containing spirally-shaped roughness were studied [43C, 54C, 66C], as well as tubes with discrete and wavy disruption shapes [38C]. There remain a number of papers in the literature which do not fit well into further subgroupings, but which generally examine the role of turbulation in heat transfer augmentation. One study considered the benefits of perturbations on a thermo Couette flow which has application to bearing design [41C]. Another study used large-scale computations to explore the optimal tubular radiator with annular fins on a nonisothermal base [50C]; finned tubes and fin arrays were also considered [37C, 42C, 58C]. Three-dimensional effects of block obstructions [44C, 48C, 63C] and radial grooves [56C] complete this subcategory.

Duct flows with secondary motion

Secondary flow can be established under a variety of circumstances, the most commonly studied being in rotating ducts, curved ducts and those where swirl is directly imposed either by injection or by using swirl generators. A significant contribution of papers in this subcategory considered the effect of secondary motion on heat transfer in rotating ducts. This configuration can be examined numerically with relative ease, and is useful in evaluating the heat transfer performance in gas turbine blade assemblies. Rotating square channels were studied with smooth walls under a variety of boundary conditions [80C, 76C] and with an oblique angle of the square to the rotation axis [77C]. Rectangular rotating ducts were also studied and including the effect of wall-transpiration [94C]. The orientation of a triangular duct to the rotation axis was found to affect the secondary vortex [72C]. Turbulent flow through a circular rotating pipe was studied experimentally using non-intrusive techniques [75C, 74C]. Rotating ducts having complex geometries were modeled using a finite volume method [71C] and studied experimentally in a smooth serpentine passage [81C]. The issue of whether analogies can be drawn between rotating pipe flows and curved ducts flows was addressed and it was shown that strong similarities exist regarding friction factor and heat transfer rates [82C]. The imbalance of centripetal acceleration and the radial pressure field causes secondary flow in curved passages. A variety of curved duct flow papers appeared in the literature. Helicoiled pipes were studied in their developing region to elucidate the origin of the non-monotonic behavior of the peripherally averaged Nusselt number [68C]. The developing, as well as fully-developed, secondary motion in a helical square duct was model numerically to address the overall increase in heat transfer rates relative to straight ducts [73C]. Effects of radius ratio [97C] and pitch [79C, 96C] were also studied. Curved ducts were studied in a collection of papers which are best categorized by their cross-section shape. Contributions included circular ducts [86C, 92C], annular concentric ducts [85C, 95C], square ducts [93C], and rectangular ducts [84C, 89C]. Swirl was imposed in a circular duct using peripheral air injection and studied using straight and slant hot wires [69C]. The decay of swirl and its connection to pipe friction factor was also investigated in a circular pipe [87C] and in a heated annulus [88C]. Swirl imposed by the insertion of twisted-tape elements was studied in a circular sectored duct; comparisons between numerical and experimental work were made [70C]. The destabilizing effect of rotation is well known in Couette flow; studies examined a heated inner cylinder [91C] and a heated outer cylinder with an insulated inner cylinder [90C]. Finally, the influence of rotation was examined in the rotor ducts of motors [83C] and in rotational cryostats [78C].

Oscillatory and pulsatile flow

Periodic or aperiodic boundary conditions can be imposed to enhance heat transfer or can be an unwanted consequence of a systemic instability which needs to be controlled. In any event, the response of the thermal field to this forcing is of vital interest. One study modeled tidal displacement oscillatory motion through low-frequency heating [100C]. Several investigations examined periodic forcing in parallel plate channels; small amplitude oscillations in channel Reynolds number were studied [103C], as well as periodic variation of the inlet temperature [101C, 102C]. Spatial variations in the solid–liquid field of a conjugate problem give rise to self-sustained oscillations which influence transport rates; local Nusselt numbers and surface temperatures are given [105C]. Pulsatile flow in a circular pipe was studied over a Prandtl number range of 100 to 12 000; the heat transfer characteristics were examined for parabolic and uniform velocity profiles [104C]. Pusaltile flow was also studied in a fully-developed curved pipe [99C] and in a thin tube or "dream pipe" [106C]. A measurement technique was explored which allows the examination of time-dependent characteristics in the duct; the approach employs liquid crystals [98C].

Two-component duct flows

Modeling of a saturated solid–fluid mixture was undertaken to evaluate the compatibility conditions for momentum and energy transport at the interface; temperature profiles were presented [109C]. The heat transfer characteristics from a solid surface to a solid–fluid suspension was considered; correlations were given for horizontal and vertical configurations [110C]. Area-averaged volumetric fractions were evaluated to assist in the modeling of thermal transport [111C]. The convective heat transfer coefficient between fluids and cubic particles was found to increase with decreasing particle size; liquid crystals were used as a non-invasive marker [112C, 113C]. The hydrate formation on the pipe wall in gaseous refrigerant R134a and water is used to evaluate heat transfer rates once a temperature distribution through the hydrate is assumed [107C]. A suspension of *n*-eicosane microcapsules was passed through a circular duct with constant heat flux; under these flow conditions the bulk Stefan number was found to be the most important parameter affecting the heat transfer rate [108C].

Non-Newtonian duct flow

A power-law fluid was studied in a vertically heated duct which is thermally and hydrodynamically fully developed [117C], and a non-isothermal die flow of a power-law fluid is examined numerically with viscous heating [124C]. "Drag reducing fluids" were studied in non-circular ducts; it was found that flow-induced anisotropic structure, not elasticity, was responsible for flow relaminarization [119C]. Heat transfer in the entrance region of a duct carrying a Herschel–Bulkley fluid was studied experimentally and theoretically [121C]. Heat transfer enhancement was demonstrated in a rectangular duct for a polyacrylamide solution relative to a constant-property fluid [123C]. A Sutterby model fluid was studied under laminar conditions in an eccentric annulus [115C] and pseudoplastic flow in rough pipes was examined [118C]. The flow of a non-Newtonian fluid through a screw extruder was computed [120C]; the effects of backflow and conduction were also considered [116C]. Measurements in a differentially-heated cavity of a non-Newtonian fluid indicate that deviations from Newtonian flow lead to large changes in heat transfer characteristics; dilatant and pseudoplastic regimes are considered [122C]. Convective heat transfer between liquid and particles in a non-Newtonian fluid was studied in a tube flow [114C].

Miscellaneous duct flows

A number of papers were concerned with the flow of Helium I and II in channels; a two-dimensional simulation was done [132C], a new test facility is described [126C] and the heat transfer in the cable-in-conduit annular channel was studied [128C]. Stratified flows were examined for managing thermal discharges [125C] and to understand turbulent flow in a flat channel [137C]. The cooling of a nozzle was studied under supersonic flow conditions using the SIMPLER algorithm [135C]. The general area of materials processing received a handful of papers in the literature. A theoretical model of extruded billets is proposed based on a kinematically admissible velocity field [133C]. A single screw extrusion process is modeled and comparisons are made to experiments [136C], and the transport of heated material in a parallel plate channel is addressed numerically [129C]. A food processing application of an N-component mixture of particles in a fluid flowing through a heated tube is examined [131C]. Blood flow in a branching countercurrent network is studied and applied to the human extremity [127C]. The laminar and turbulent flow within oil seals is considered [134C] as well as laminar thermosolutal convection in a two-dimensional trapezoidal cavity [130C].

FLOW WITH SEPARATED REGIONS

Separated flows were subcategorized loosely as follows: bluff objects and their associated thermal wake; jet and mixing layer flows; and confined separated flows. Endwall heat transfer was studied in the neighborhood of a boundary layer fence [20D]; similar issues were addressed at a much larger scale where building facades were simulated and modeled in the laboratory [10D]. An array of rectangular electronic modules positioned in a uniform flow stream was examined; in particular the wake scaling was documented [9D]. Cylinders in crossflow continue to fascinate the world of fluid-thermal scientists and engineers; single and multiple cylinder systems were studied. The spanwise structure in the wakes of single and tandem cylinders were examined to evaluate their impact on convective heat transfer rates [23D]. An in-line array of rectangular modules was studied to determine whether correlations could be developed between the convective heat transfer rate and the associated thermal wake [12D]. Steady state convection from fin arrays was examined in a number of papers. Horizontal pin-fin assemblies were studied experimentally; geometric effects were investigated [22D]. Two-phase flow past tube banks was used to evaluate heat transfer rates using the analogy between heat and mass transfer [8D]; void fraction along a vertical heated rod bundle was also considered [18D]. Other fin arrays studied included interrupted longitudinal fins [14D] and convex louvered fins [15D]. Bluff object flow was also examined under hypersonic conditions; convective heat transfer [21D] and shock characteristics [5D] over blunt nose bodies were presented.

The turbulent integral scales in jets and diffusion flames were studied using a cross-beam Schlieren system; similarities were found between integral scales for both mixing and reacting flows [7D]. An examination of Taylor's hypothesis was undertaken in a slightly heated circular jet to consider the local isotropy of the flow [11D]. Jet impingement was investigated in the context of splattering during liquid jet interaction with a solid surface [3D] and with regard to the interaction of the impinging jet with extended surface modifications [17D]. Opposing heated jets were studied in a confined crossflow; thermal mixing characteristics were enhanced at higher momentum flux ratios and incident angle [4D].

The final group of papers concerns those flows experiencing a rapid change in confined area. The scaling of the fluid-thermal features in large stratified volumes was addressed; injected buoyant jets, plumes and wall jets were imposed [16D]. As semi-finite aquifer was modeled to evaluate the resulting temperature field [13D]. The flow over backward and forward facing steps as well as in a two-dimensional channel was modeled using an improved low-Reynolds number k–ε model [6D]; new turbulent modeling was also employed to compute the recirculating zone caused by a backward facing step [1D]. Buoyancy-opposing laminar flow over a backward facing step was studied; velocity and temperature distributions are reported [2D]. A heated cavity flow was considered in a modeling effort; the single vortex within the cavity was not found to affect the flow external to the cavity [19D].

HEAT TRANSFER IN POROUS MEDIA

Introduction

The scope of research on heat and mass transfer in porous media continues to expand owing to two pervasive trends. The first is the increasing applicability of porous materials in a wide range of engineered products and manufacturing processes. Secondly, analytical and numerical techniques are being developed and used that are much more powerful than in the past. These techniques make it possible to work at either the pore or particle level and, in some cases, remove the requirement of local thermodynamic equilibrium between the solid and fluid phases.

Research generally falls into several broad categories in this area and these include.

- Property determination, including transport properties.
- Flow and heat transfer in stationary porous media.
- Packed beds, including moving beds and fluidized beds.

The literature this past year also indicates that experimental studies are gaining in complexity from two aspects: (1) more difficult, multicomponent, multiphase systems and transport processes are being investigated; and (2) local measurements are being attempted with much greater regularity than in the past.

Property determination

Determining the thermophysical properties of saturated porous media has continued to receive both theoretical and experimental attention. Reviews of existing models have continued to appear [1DP] in connection with a diverse range of technologies. Contributions to the literature have treated both random and structured, i.e. periodic, media [5DP] and single and two-phase systems [9DP] have been studied. The radiative properties of porous and fibrous media have taken on new importance as high porosity composites, aerogels and porous wall materials are gaining in application [4DP, 2DP, 7DP, 6DP].

Theoretical work has employed the modified Zehner–Schlunder models for stagnant thermal conductivity [3DP] of saturated media and compressible flow in porous media has been analyzed via an exact solution employing a distance-dependent expression for permeability [8DP]. A new model for the effective thermal conductivity of porous pellets have been developed in connection with steel making technology [10DP].

External flow and heat transfer

Flow in a porous medium external to either an impermeable or permeable wall has received analytical and experimental study. Wedge flows for both Darcy and non-Darcy cases have taken into account variable free stream conditions and inertia [16DP]. Numerical work has appeared on natural convection in the presence of an impermeable surface [17DP, 18DP, 19DP]. Both heat transfer and flow structure effects of the wavy surface have been determined.

Forced and mixed connective flows over a flat plate have been studied in an attempt to define dimensionless heat transfer coefficients as function of the relevant dynamic parameters [21DP, 22DP, 11DP, 12DP, 14DP, 15DP]. One study has considered buoyancy-affected couett flow past a highly porous wall [13DP]. Another has considered free convection one a vertical porous plate with suction and hydromagnetic effects [20DP].

Packed beds

Research on packed beds has continued to expand in several directions. In this broad subcategory are included moving beds, fluidized beds and stationary packed beds and columns. Heat and mass transfer studies this past year have investigated a wide range of topics handling the fundamentals of flow in the bed of heat and mass transfer associated with desiccant dehumidifiers.

Studies of the fluid mechanics have addressed overall skin-friction relations [49DP] and back mixing [35DP]. Flow structures in stationary and moving beds with heat transfer have been investigated for a variety of situations and in many cases the fundamental characteristics, or properties, of the bed have been described, e.g. thermal parameters for the bed, single particle heat transfer and turbulence characteristics [27DP, 38DP, 26DP, 29DP, 39DP, 50DP, 25DP, 30DP, 45DP, 40DP, 28DP]. Several studies have sought to develop the general characteristics of heat transfer in gas–liquid, gas–solid, and gas–liquid–solid systems [37DP, 43DP, 48DP, 24DP, 32DP]. In this vein, there has been continuing interest in combustion-related work [41DP, 42DP].

Wall heat transfer in packed and fluidized beds has appeared as a topic of special interest to a number of research groups, and analytical and experimental studies are developing a more complete description than exists of the fundamental topic [44DP, 31DP, 46DP, 36DP, 23DP, 33DP, 47DP, 34DP].

Porous layers and enclosures

A variety of very fundamental studies of heat and mass transfer in saturated, stationary porous layers have appeared this past year. Some have included internally heated layers [68DP, 70DP, 60DP, 59DP]. For many studies, buoyancy driven convection has been the focal point and a range of important stability and transport mechanisms has been investigated [73DP, 54DP, 55DP, 56DP, 61DP, 65DP, 66DP, 72DP, 58DP, 57DP, 62DP, 63DP, 64DP]. New fundamental work has also appeared on wall boundary conditions for both flow and heat transfer [69DP], dispersion [67DP] and coupled transport processes [51DP]. Specialized studies have appeared of heat transfer in the melting of frozen porous media [71DP, 74DP, 75DP] and also in freezing of initially wet media [52DP].

Coupled heat and mass transfer

Coupled heat and mass transfer processes have continued to receive attention in connection with drying [80DP, 77DP, 76DP], solvent evaporation in dense polymers [81DP], and porous flame holders [79DP]. One study [82DP] developed a non-linear analysis of heat and mass transfer using a potential-based model. Fundamental work on the convective instability of moist gas in porous media was reported [83DP].

Miscellaneous studies

A variety of technologically motivated studies of heat and mass transfer in porous media have added both fundamental and applied knowledge to the literature. High temperature nuclear heat transfer using pebble beds was the focus of two studies [90DP, 85DP]. Transport processes in porous media as they related to geophysical heat transfer also received attention [84DP, 91DP, 86DP, 88DP, 89DP, 87DP]. In these studies, the focus has been on environmentally motivated problems, such as pollutant transport, *in situ* combustion and ground water hydrology.

EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

Many experimental results are cited in other categories of this review. The purpose of this section is to identify papers that focus on new or improved experimental measurement techniques or devices that are useful in experimental studies of heat transfer. The publications referenced here deal explicitly with some aspect of heat transfer measurement or include a general review of techniques that are applicable to heat transfer measurements.

Heat transfer measurements

Surface heat flux in a gas was deduced directly from laser beam deflection [3E]. A series of papers discussed calibration and the need for improved standard methods for surface mounted heat flow meters [4E, 2E, 7E, 6E]. Other heat flux sensor applications included transient measurements of building structures [1E] and combined thermal and moisture transmission measurements [5E]. Methods to determine the effects of aging on thermal insulation [2E] and for the entire heat transmission coefficient for insulated vehicles were given [8E].

Temperature measurements

Several papers discuss novel temperature sensors [18E, 22E, 24E], measurement errors [14E] and applications [15E]. Fluid temperature distributions have been measured with various nonintrusive optical approaches including Schlieren [13E], interferometry [20E, 23E] and laser-sheet-illuminated Rayleigh scattering [19E]. Surface temperatures have been measured using liquid crystals [16E, 21E], infrared radiation [9E, 10E, 11E, 17E] and laser-induced fluorescence [12E].

Velocity measurements

Considerable work continues in characterizing hot wire/film anemometers [31E, 32E, 36E], particularly their ability to measure three-dimensional velocities [33E]. Methods to measure fluid temperature and velocity simultaneously have been reported [27E, 35E]. Optical velocity measurements include advances in laser Doppler anemometry [25E], particle image velocimetry [26E, 34E] and laser Doppler shifting [30E]. Other developments include a velocity sensor for liquid metals [29E] and an integrated mass flow sensor [28E].

Thermophysical properties

Several authors report novel methods to measure thermal conductivity [40E, 41E, 45E], specific heat capacity [42E], thermal diffusivity [37E, 38E, 44E], or more than one of these properties simultaneously [39E, 47E]. Methods to determine thermophysical properties of solids were presented [43E, 46E].

Miscellaneous methods

Measurement methods that do not fit any of the categories above are included here. These include tomographic methods [50E, 51E], remote sensing [49E, 52E], thermal impedance of lasers [48E] and biological applications [53E].

NATURAL CONVECTION—INTERNAL FLOWS

Natural convection in internal flows has continued to receive interest from a number of fundamental and applied perspectives. Research in this field has largely been numerical over the past year, and the availability of commercial codes to solve the governing equations of change portends even more activity in this direction. Nevertheless, several experimental studies are reported, and classical methods of measurement of temperature are yet largely used. Flow visualization and Zhender–Mach interferometry have been used to obtain flow field information. Generally, there appears to be little in the way of validation of numerical predictions.

Fundamental studies have focused on details of flow structure and stability, and turbulence modeling has been introduced in certain cases. Natural convection in heat generating fluids and thermocapillary convection have been considered from a fundamental perspective. Materials manufacturing, specifically the processing of electronic materials and crystals has led to a number of articles emphasizing buoyancy dominated convective flows. Enclosure and channel flows also continue to receive attention, but work has shifted to focus on complex geometries in which diathermic partitions determine the overall character of the flow.

Fundamental studies

Fundamental contributions to understanding the heat transfer and flow processes in natural convection continue, although at much lower rate than in previous years. Numerical studies of both laminar and turbulent flows have been reported for two- and three-dimensional enclosures in which thermal boundary conditions are well specified [21F, 11F, 12F, 17F, 13F, 19F, 2F]. Such works have brought to light details of both steady, oscillatory and non-steady systems. Both the bifurcation and the stability of the flow under various heating conditions have continued to receive attention [20F]. A few studies have begun to appear of natural convection in fluid where compressibility cannot be ignored [3F, 4F]. One experimental study [16F] on natural convection in water near its density maximum was reported. Binary mixture flows in a horizontal layer were considered, to determine flow stability under a variety of heating conditions [8F].

Turbulence modeling of natural convection flows received a good deal of attention as well. Buoyancy driven internal flow and jet flows were examined. Both two- and three-dimensional flows have been studied, thanks largely to the capabilities that modern computers bring to researchers. Turbulent cavity flows received the most attention [6F, 10F, 1F, 5F, 9F, 14F, 7F]. Bouyant jet flows were studied by two groups [15F, 18F].

Heat generating fluids

Free convection in cavities where internal energy generation drives the flow continues to receive attention. Such flows arise in connection with nuclear power [26F, 25F, 24F] and environmental applications [22F, 23F].

Thermocapillary convection

Of particular interest has been convective systems in which thermocapillary and surface tension effects are present. Such systems have been investigated in connection with the manufacturing and processing of electronic and other materials. The literature contains studies of Benard–Marangoni instabilities [32F, 34F, 37F, 39F, 29F, 33F, 31F, 41F] in enclosures of general applicability. Extensions to include the Soret effect [27F], effects of solidification [30F, 40F] and electrophoretic effects [36F] have been reported. Research efforts on specialized systems have also begun; these included the Benard–Maragoni instability driven by a heated divider [28F], thermocapillary convection with non-uniform magnetic fields [35F] and instabilities in layers with internal energy generation [38F].

Enclosure heat transfer

Experimental studies continue to be few in number but those reported have added fundamental data to our knowledge of heat transfer from inclined parallel plates [53F]. Variations on the problem of computing natural convection in laterally heated cavities were treated by [42F, 54F, 49F, 50F, 48F]. More general rectilinear cavities, e.g. parallelograms and trapezoids were treated by [46F, 43F, 47F]. Inclined enclosures were considered by [52F]. Discrete heating in a rectangular enclosure was studied by [44F, 45F]. The effects of a hemispherical lower boundary on natural convection in a layer were reported by [51F].

Vertical duct flows

Buoyancy driven flows in vertical ducts and tubes were investigated to determine wall heat transfer. Geometries that received attention included open vertical tubes, staggered vertical channels, and a finite length channel in free space [56F, 58F, 55F]. Conjugate natural convection was also considered for a vertical annulus [57F].

Horizontal cylinders and annuli

Free convection flow and heat transfer in a variety of geometries, generally classed as horizontal cylinders and annuli, received continued interest during the year. As with cavity flows, most work reported was numerically based with a focus on the details of the flow and temperature fields. Experimental research for this geometry appears limited. For vertical annuli, correlations between Nusselt and Rayleigh numbers have been obtained for a wide range of Prandtl numbers [59F, 62F, 60F, 63F]. Horizontal cylinders and annuli were treated by several authors to yield similar heat transfer results [65F, 64F, 66F, 61F].

Mixed convection

Mixed convection in buoyancy-dominated situations received both experimental and numerical treatment. Measurements of wall temperatures in a cylindrical duct using infrared thermography were presented [67F]. Analytical and numerical studies of a variety of flows in channels and tubes were also presented [75F, 72F, 69F, 68F]. One study [70F] treated power-law fluids in mixed convection in a vertical duct. In all of these studies, results include temperature and velocity profiles, and Nusselt numbers in terms of the dominant dynamical parameters. Another study [71F] has treated a horizontal semicircular duct with axially nonuniform thermal boundary conditions. Mixed convection in shallow horizontal and narrow vertical cavities was also treated [73F, 74F].

Complex geometries

Natural convection in a wide range of complex geometries has been studied with respect to specific technological applications. Complexities have been generally introduced by the presence of baffles, internal fins and conducting partitions [76F, 77F, 79F, 80F, 82F, 83F, 84F, 85F, 87F, 88F, 89F, 90F]. Experiments on natural convection through an aperture in a partitioned enclosure were also reported [86F]. Flow visualization studies and numerical analysis of natural convection driven by heated cylinders, contained in an enclosure, provided valuable information on the flow field and heat transfer from the cylinders [78F, 81F].

Fires

Natural convection in fires continued to receive wide spread attention, and both experimental and numerical work continues in industry, government laboratories and universities. Three review articles summarize the state of numerical modeling for both fire spread and pool fires [97F, 91F, 98F]. New research results on the mechanisms of fire spread have been reported for pool fires [96F, 93F]. Fires in mines [94F], the ignition of evergreen trees [92F], smoldering combustion [99F] and heat transfer ceiling jets [95F] were also treated numerically and experimentally.

Miscellaneous topics

Materials processing continues to receive attention as a specialized topic within the larger context of buoyancy and surface tension dominated flows. Numerical results for velocity and temperature fields have been presented on three-dimensional gravitational and solutal effects in a cylindrical cell [107F], flow instability of the melt during Czochralski Si crystal growth [103F], and interface shapes in a floating molten zone [104F, 105F]. Environmental flow and heat transfer, involving natural convection, has been treated numerically for transport near the critical point of water in a porous system [102F]. Thermosyphon and capillary pumped loops also received attention [101F].

Heat transfer in ceramic monoliths was studied experimentally to determine the influence of void fraction on wall temperatures [108F]. Electronic equipment and chip cooling received attention in a numerical study of immersion cooling of a substrate-mounted protrusion in a three-dimensional enclosure [109F]. Results of an analytical study of hot spots on ventilated dry-type transformer windings were reported [106F]. The thermal analysis of floor heating panels was treated numerically, and shape resistance factors were determined [100F].

NATURAL CONVECTION—EXTERNAL FLOWS

Vertical flat plate

Natural convection from a vertical plate remains a subject of interest to a variety of investigators because of its relative simplicity, the possibility for considering a number of variations on the boundary conditions (including surface structure) and its importance in real systems. Studies include experiments with a constant heat flux, boundary condition (including turbulent boundary layer flow) [6FF], numerical solutions for heat transfer to a surface with constant heat transfer coefficients [9FF], and the influence of unheated starting layers [8FF]. Variations of surface contour considered include vertical wavy surfaces with transient laminar flow [3FF], the influence of a backward facing step [7FF], and the effect of a microgrooved surface [15FF]. Other papers consider enhancement of heat transfer using horizontal extensions [10FF, 13FF, 14FF], overlapping segments [2FF] and gas injection and/or suction [4FF]. Still other influences considered include very high wall temperature [11FF], convection from an L-shaped corner [1FF] and the influence of Hall effects when there is a transverse magnetic field and a conducting fluid [12FF]. Means of discouraging drafts from vertical walls in rooms have been considered [5FF].

Horizontal and inclined plates

Studies on convection along horizontal surfaces include models for flow above polygon-shaped surfaces [20FF], the influence of variable viscosity on flow instability [18FF] and Soret thermal-diffusion factor influences [19FF]. Convection on horizontal and also vertical surfaces within buildings has been examined [15FF]. A finite difference approach provides solutions for transient convection on an inclined plate [17FF].

Cylinder and sphere

Studies on convection from horizontal cylinders include the influence of conduction in the cylinder body (conjugate problem) [26FF] and convection over a range of laminar and turbulent flows for cylinders of noncircular cross-section [22FF]. Correlations have been provided for air cooling of spherical and cylindrical objects, including fruits and vegetables [23FF]. Flow and heat transfer around cylinders with convection fins [24FF] and a cylinder between confining plates [28FF] were examined. Heat transfer from more than one horizontal cylinder has been considered including the effect of vertical separation distance between two cylinders and the interaction of their flow fields [30FF, 27FF]. General arrays of cylinders have also been considered [29FF]; the interaction between the cylinders plays an important role [25FF]. Experiments provide correlations for convection from helical coiled tubes [21FF].

Buoyant plumes

A study of the structure of buoyant plumes provided experimental flow correlations over a range of heights above the heat source considering, in particular, the self-preserving portion of the flow [32FF]. Characteristics of plumes as would be applied to pipes in a greenhouse have been discussed [31FF]. Experiments have been conducted on turbulent buoyant jets of liquid sodium [33FF].

Mixed convection

Analogies have been developed for mixed convection on vertical and horizontal flat plates [35FF] at moderate and high Prandtl numbers. A numerical investigation used a special coordinate system for mixed convection from a circular cylinder [34FF]. An analysis considered mixed convection to power-law fluids over arbitrarily shaped two-dimensional or axisymmetric bodies using a series expansion technique [36FF].

Miscellaneous

A number of other geometries have been considered including measurements with arrays of isothermal triangular fins [40FF] and measurement and numerical solution for flow of a power-law fluid around a vertical frustum of a cone [39FF]. Experiments on flow around fins confirmed an earlier theoretical model [37FF]. Special flows include influence of an induction electrohydrodynamic pump [43FF] and the influence of slight perturbations of the gravitational body force [38FF]. An analysis considered procedures for obtaining interferometric data as often applies to natural convection studies [42FF], while a conjugate analysis described heat and mass transfer during drying of foods [41FF].

CONVECTION FROM ROTATING SURFACES

Rotating disks

Studies of single rotating disks include the effects of smooth and grooved surfaces with impinging flow normal to the disk surface [7G, 5G, 3G]. Laminar mixed convection between two co-rotating disks has been studied numerically [14G]. Several papers address the issue of heat transfer in a cavity formed by co-rotating disks and a shroud with axial flow of air that approximates a portion of a gas turbine engine [11G, 12G, 13G, 9G, 15G, 1G]. Several different flow patterns were observed between two counter rotating disks depending on the magnitude of the governing parameters [4G, 8G]. Another geometry that has been investigated is a rotating disk with a stator [2G, 10G].

Rotating channels

The study of rotating channels has been motivated primarily by the use of coolant passages in gas turbine engine components. Numerical solutions have been obtained for the flow and heat transfer in rotating channels of rectangular and square cross section [22G, 16G, 23G]. Experiments have been performed on channels of multipass or serpentine geometry [18G, 19G, 20G]. Other investigations considered flow and heat transfer in an open loop [21G] and a cylinder open at one end rotating about its axis [17G].

Enclosures

Two papers reported theoretical studies of the heat transfer in rotating cylinders [30G, 26G]. An experimental study was performed on filled, rotating food cans undergoing heating [29G]. Other investigations considered rotating rectangular enclosures and a rotating fluid layer [27G, 24G]. Numerical solutions were presented for rotating annuli with circular or square cross-section [25G, 28G].

Cylinders, spheres, bodies of revolution

A theoretical study was made of rotating axisymmetric bodies with uniform suction or injection [32G]. Additional theoretical work was performed on a rotating cone and a hot wire anemometer [31G, 33G].

Miscellaneous

Other work includes flow inside a rotating droplet, effects of swirl on combustion, measurements of heat transfer in rotating gas turbine engine components and rotating plates and contoured surfaces [36G, 38G, 34G, 37G, 39G, 35G].

COMBINED HEAT AND MASS TRANSFER

Ablation—transportation

A number of studies consider ablation from localized high energy sources of radiation, namely pulsed lasers, with analysis of the material loss and heat transfer. These analyses include the solution of one-dimensional equations for determining the temperature at which ablation starts [4H], the loss of material from thin silicon wafers, and the introduction of material into a substrate to enhance ablation [2H]. Consideration of the production of polymeric optical waveguides considered ablation rates of different polymeric materials [3H]. Analyses of ablation included using a Landau transformation of finite control volume procedure [1H] and a finite element model for determining heat transfer and material loss [6H]. Consideration of the relationship between transpiration cooling and full coverage film cooling compared well with experimental results [5H].

Film cooling

Film cooling continues to draw the interest of many investigators partly because of its wide spread application in modern high temperature gas turbines where it is used to protect not only combustion chambers but also the high temperature stages of turbines both in the stationary veins and the rotating blades. The influence of a number of factors on film cooling have been examined including effects of freestream turbulence [9H], and wall curvature, both positive and negative [11H]. The influence of orientation of axis of the holes through which film coolant is added is an important factor. Compound angle orientations have been considered for different spacings between holes and a number of rows [16H, 17H]. The discharge coefficients for such injection have also been examined [12H]. With a compound angle the effects of embedded longitudinal vortices [15H] have a strong influence on the film cooling effectiveness and heat transfer [14H]. Film cooling of the stagnation region of a circular cylinder [10H] and the leading edge of a turbine blade have been examined experimentally [18H]. Film cooling of a rotating blade has been shown to reduce the time averaged heat transfer [7H]. Film cooling in a supersonic flow up to a Mach number of 2.4 indicates that helium is a more effective coolant than is air [13H]. A simple measure of film cooling performance has been described to aid in preliminary design analysis [8H].

Submerged and free jet cooling

Studies on the heat transfer to or from impinging jets include a number of experimental, numerical and analytical studies concerned with the characteristics for single jets, arrays of jets, different impinging surfaces, jet geometries, etc. Experiments include measurements for impingement at low jet to surface distances and measurements that include low Reynolds number flow [33H, 27H]. Analyses include prediction of the heat flux characteristics along the jet flow [36H] and finite difference analysis of heat transfer from an impinging jet with transient thermal boundary conditions on the surface [19H], and the hydrodynamic conditions of the surface on which the jet impinges [22H]. Heat transfer from an impinging jet to a surface with roughness elements [34H, 35H] and the heat transfer with a jet from an elliptical nozzle [32H] and a rosette nozzle [30H] have been measured. Other influences considered for single jet impingement include effects of exciting the jet [25H] and using a pulse jet [20H]. Studies of two-dimensional slot jets include experiments over a range of Reynolds numbers and separation distances [24H], a numerical analysis [23H], the effect of interaction between adjacent slot jets [37H], and a comparison of heat transfer for a slot jet and a row(s) of circular jets impinging on a concave surface [21H]. In many applications arrays of circular jets are considered. Studies on heat transfer with such arrays include experiments over a range of conditions [38H], transient measurements on the heat transfer under an array [39H], effect of spacing between jets [29H] and the different effects that occur for jets on the outer portion of an array [28H]. Applications considered include cooling of steel strip, turbine disk cooling and drying of paper [26H, 31H].

Liquid jets

Liquid jets have great capacity for cooling because of their greater density, conductivity, and heat capacity per unit volume. Heat transfer to or from liquid jets has been considered in studies considering jets of a molten metal [40H, 41H], cooling of a direct-fired surface [43H], and cooling of electronic components [47H].

Other studies on applications with liquid jets include consideration of the high temperature jet of a molten material [42H], arrays of liquid jets to cool a chip-like electronic surface [50H], and the influence of wall roughness on the stagnation region heat transfer beneath a liquid jet [45H]. Another study considers the translaminar and turbulent regimes following liquid jet impingement on a surface [44H]. Heat transfer from a multiple array of slot jets with laminar flow has been examined numerically [49H]. Studies on wall jets include numerical analysis for a laminar cylindrical wall jet [46H] and for arrays of turbulent impinging slot jets [48H].

Drying

Drying continues to be an important issue in many applications, particularly in the production of films and in the food, grain, and paper industries. Modeling and drying of solvent coatings on continuous webs [56H] and polymer films [66H] have been described. Drying issues in foods include studies related to peanuts [52H], rice [61H], biscuits [51H], grain [54H], carrots and potatoes [63H], and wheat [59H]. Other important areas of application in drying include wood [58H, 55H, 64H], coal piles [53H], tobacco particles [60H], non-woven fabrics [67H] and magnetic tape packs [65H] have been described. Heat/mass transfer issues in desiccant materials [62H, 57H] have been modeled.

Miscellaneous

Recent studies include those on heat and mass transfer on a coupled drying and heating system [72H], in a radial creeping flow [68H] and in multicomponent flow [70H]. The importance of combined heat and mass transfer in fibrous insulation [73H] and porous pellets [74H] has been explored. Studies on falling liquid films [71H] and the influence of an electrical field [69H] have been reported.

CHANGE OF PHASE—BOILING

Thermal transport phenomena associated with liquid-to-vapor phase change are addressed in the publications reviewed in this section and classified into four major categories: droplet and film evaporation (25 papers), bubble characteristics and boiling incipience (13 papers), pool boiling (47 papers), and flow boiling (52 papers). In addition to these 137 papers, dealing with evaporative and ebullient heat transfer, the interested reader will find reference to these phenomena in some papers included in: change of phase—condensation (JJ); heat transfer applications—heat pipes and heat exchangers (Q); and heat transfer applications—general (S).

Droplet and film evaporation

The evaporation of droplets is of importance in understanding and predicting the behavior of atmospheric aerosols, combustion of liquid fuels and spray cooling. Models and predictions for evaporation from small, isolated drops, which underpin many of the applications in this field, continue to enrich the literature. During this review period, attention was devoted to the development and refinement of an analytical model for a single evaporating drop adhering to an impermeable wall [3J], theoretical studies of liquid–solid contact angle hysteresis [21J], the gathering of empirical data for an evaporating drop suspended from a quartz tube [22J], and quantification of the enhancement of droplet evaporation by the presence of a static electric field [24J]. Numerical investigations of time-dependent evaporation rates from a stationary droplet [10J], from water droplets injected into a gaseous stream [7J], a translating droplet with internal circulation [9J], and from a deforming, translating droplet at intermediate Reynolds numbers [13J, 14J], can also be found in the literature, along with a proposed simplification for the computation of evaporation and combustion of a single droplet [18J]. An analysis of the factors affecting feed droplet evaporation in fluidized catalytic cracking risers is presented in Ref. [4J] and a model which describes the evaporation, ignition and combustion of a drop cluster in a large vortex is discussed in Ref. [8J]. Heat transfer rates from droplets in the microgravity flow of air–water mixture were reported in Ref. [20J].

Thin film evaporation is encountered in refrigeration, distillation and desalination equipment, as well as underneath growing bubbles and along channels experiencing high vapor-fraction ebullient heat transfer. [11J] explores the effects of lateral conduction on microlayer evaporation beneath a bubble during nucleate boiling, [1J] presents an extension of the basic two-dimensional, laminar, thin-film model to inclined plates, and [2J] explores flash evaporation under low pressure. Evaporation of a thin film flowing in a V-shaped microgroove was the subject of Refs [12J, 23J] and the pressure drop in such a microgroove is described in Ref. [17J]. Binary mixture evaporation was studied in Ref. [19J], with emphasis on interactive heat- and mass-transfer phenomena in falling film evaporation of ethylene and propylene glycol and in Ref. [16J], where unsteady sprays, approximating diesel engine conditions, were of interest. The beneficial effect of a thin layer of insulating material on mist cooling was recorded in [15J]. Evaporation in the environment was addressed in several studies, including: [6J]—which explored evaporation beneath an [atmospheric] convective boundary layer; [26J]—which developed a sophisticated model of evaporation from the soil, and Refs [5J, 25J] which describe vapor generation rates during liquid spills.

Bubble characteristics and boiling incipience

Studies of the formation, growth, and departure of vapor bubbles are essential to a greater understanding of ebullient heat transfer and two-phase flow. Boiling nucleation by rapid heating was reported in Refs [28J, 38J] and by flash boiling in Ref. [34J]. In Ref. [37J] liquid crystal thermography was used to study the spatial and temporal temperature variations on a surface experiencing boiling incipience. The vapor temperature and pressure variations associated with the deactivation of nucleation sites, upon cooling, and in an oscillating bubble were examined in Refs [29J] and [35J], respectively. The numerical simulation of vapor bubble growth in a superheated binary solution was described in Ref. [33J], the motion of a single bubble in Ref. [32J], and the contribution of thermocapillary convection in Ref. [36J]. Bubble interactions in pool boiling were examined in Ref. [30J], while Refs [39J, 27J] discuss aggregate bubble characteristics in subcooled flow boiling. Bubble-induced heat transfer in a molten reactor core is described in Ref. [31J].

Pool boiling

Archival publications in pool boiling continue to reflect the recent focus on new applications, unconventional fluids, unique geometries and various enhancement techniques, as well as a renewed interest in fundamental aspects of ebullient heat transfer. Several new models were proposed for nucleate pool boiling, including: [75J]—which uses only bubble site densities and departure diameter data to predict the heat transfer coefficient; [45J]—which develops a "sliding-bubble" correlation for horizontal tubes; [56J]—which uses thermodynamic similarity to estimate the boiling characteristics of poorly known fluids; and [41J]—which argues that nucleate boiling heat flux varies linearly with surface superheat. While a two-phase mixture model was used to numerically investigate boiling in porous layers in Ref. [82J], the experimental results for thin powder layers in Ref. [86J] were interpreted in terms of a micro-thermosyphon model.

Pool boiling of cryogenic liquids was explored in Ref. [54J]—which provides experimental data for pool boiling of helium from a copper plate, applicable to low-temperature superconductors; and Refs [65J, 66J] which describes studies of the pool boiling of nitrogen from ceramic copper-oxide surfaces, typical of high-temperature superconductors. The character of cryogenic liquid boiling at a current-carrying point contact is explored in Refs [43J] and [77J] presents detailed experimental data for pool boiling of R-113 from a power transistor. The boiling of stirred, viscous liquids is discussed in Ref. [46J] for Newtonian liquids and in Refs [48J, 51J] for non-Newtonian liquids. Reference [78J] describes the results of an experimental and analytic study of the saturated nucleate boiling of mercury, in the presence of a magnetic field. Heat transfer in the boiling of binary mixtures is the subject of Ref. [44J]—providing correlations and a detailed review of pool and flow boiling data, of Ref. [74J]—where emphasis is placed on the influence of mixture composition on bubble properties and of Ref. [49J]—highlighting the development of an improved correlation. The boiling of liquid oxygen, liquid hydrogen and liquid nitrogen mixtures, in a pool of fuel or simulant, and of refrigerant–oil mixtures, in a confined space, were described in Refs [60J] and [63J], respectively.

Pool boiling under microgravity conditions, in which surface tension effects become significant, attracted the attention of several investigators. In Refs [76J, 73J] it is argued that thermocapillarity and "vapor recoil instability" in the evaporating microlayer can compensate for the loss of buoyancy, in Ref. [64J] emphasis is placed on quasisteady boiling made possible by surface rewetting, and in Ref. [40J] Marangoni flow is used to explain improved microgravity heat transfer for non-azeotropic binary mixtures. Enhanced nucleate boiling heat transfer—through the use of porous coatings and studs is reported in Refs [79J] and [67J], respectively—through the use of fins and rib-roughened tubes in Refs [57J] and [52J], respectively—with additives in Ref. [58J], with electrohydrodynamic forces in [42J] and by surface oscillation in Ref. [81J].

The so-called critical heat flux [CHF], occurring at the transition from nucleate boiling to film boiling, is generally accompanied by the formation of a vapor blanket over the surface. The application of catastrophe theory to CHF is discussed in Ref. [61J]. Observations on the formation and behavior of the pre-CHF vapor mass, along a large, vertical surface were described in Ref. [55J], experimental data for CHF on a submerged hemisphere in Ref. [80J], for sub-millimeter horizontal cylinders in Ref. [85J], and CHF in aqueous surfactant solutions in Ref. [84J]. Ref. [83J]—reports on the measurement of the peak heat flux densities for subcooled superfluid helium. Heat transfer during quenching of steels was the subject of several studies, including Ref. [59J]—examining quenched cylinders experiencing simultaneous film and pool boiling as well as convection; [70J]—reporting on the microstructure and mechanical properties associated with various procedures; and [62J]—focusing on the development of residual thermal stress. Steady pool transition boiling is the subject of Ref. [53J]. References [71J, 72J] explore the effects of thermophysical properties on laminar and turbulent film boiling, respectively. Reference [68J] reports on experimental results for large diameter horizontal and long vertical cylinders. Film boiling heat transfer during a catalytic decomposition reaction is described in Ref. [69J], during rapid depressurization in Ref. [50J], and on a moving isothermal surface in Ref. [47J].

Flow boiling

In convective or flow boiling, the enthalpy of the coolant and the state of aggregation of the vapor, as well as the orientation of the channel and the geometry of the heated surface, all influence heat transfer at the wall. Horizontal-pipe flow boiling of helium in several distinct flow regimes and of subcooled R-11 were studied experimentally in Refs [124J] and [93J], respectively. The injection of cold liquid water into a hot air stream, flowing in a small diameter tube, was examined experimentally in Ref. [106J], and of immiscible mixture in [108J]. The flow boiling characteristics of microchannels were described in Ref. [127J], flow boiling in channels with divertors, planned for use in fusion reactors, in Ref. [95J]. Heat transfer rates for convective boiling of mixtures were examined in several archival publications, including: mixtures of SF6 and CCL2F2 in Ref. [125J], and binary mixtures of acetone-, isopropanol- and *n*-butanol-water in Ref. [133J, 139J, 140J]. An experimental investigation of the pressure drop in two-phase liquid metal flow of potassium was reported in Ref. [128J].

Flow boiling data obtained in an industrial cryostat was presented in Ref. [90J]. Scaling laws for two-phase flow heated by a nuclear fuel rod are discussed in Refs [91J] and [96J] a numerical model of conjugate heat transfer in a boiling tube was used for analyzing and scaling high flux, flow boiling. In Ref. [126J] large three-dimensional numerical codes were used to simulate a steam line break in a pressurized nuclear reactor. Enhancement of flow boiling heat transfer rates were examined in Ref. [141J]—which describes two-phase flow in a lunate channel; and Ref. [120J]—which discusses the mechanism for turbulent two-phase heat transfer in tubes with twisted-tape inserts. [129J, 130J, 138J, 110J] all explore the flow boiling behavior of refrigerant mixtures in enhanced surface tubing. Thermally-induced flow instabilities, associated with parallel boiling channels [121J], with a step-change in power [118J], heat flux variations in the presence of inlet and outlet restrictions [116J], and changes in the buoyancy force within the liquid, resulting from subcooling [105J] or dissolved gas [102J], were also reported in the literature.

A considerable number of flow boiling papers published in 1994 deal with the modeling of critical heat flux (CHF) or dryout in flow boiling in channels. Among these are: [131J] presenting an analytic model based on a postulated thermo-mechanical effect, [122J] proposing a predictive model relying on the use of fuzzy logic, [132J] re-affirming the importance of CHF even in the presence of conjugate effects, [97J, 117J] assessing the available models, approaches, and correlations appearing in the literature and used in commercial codes, [99J] deriving a new "dryout" model free of empirical constants, [104J] offering a new approach to predicting the minimum value of CHF, and [137J] presenting a phenomenological model for CHF in tubes containing twisted-tape.

Experimental studies of channel CHF and dryout in this convective boiling regime, include: [135J] providing data and a new statistical correlation for very high heat fluxes, [114J, 87J] reporting on the relationship between the hydrodynamic regimes and CHF, [100J] determining the dependence of the CHF location on various thermofluid parameters, [134J] describing results for low and medium pressure; and [94J] exploring the effect of bouyancy on CHF along a flat surface. Enhancements of CHF on finned fuel elements are examined in Ref. [115J], for tubes with turbulence promoters in Ref. [109J], for fuel assemblies with mixing vanes in Ref. [103J], for mini- and microchannels in Ref. [92J], and for tubes using helically coiled wires in [98J]. A correlation for CHF in the presence of density-wave oscillations and data for CHF in binary refrigerant mixtures can be found in Refs [136J] and [101J], respectively.

Flow boiling behavior, at fluxes greater than associated with critical heat flux (CHF), takes several forms. Post-CHF heat transfer in dispersed droplet swirl flow is modeled in Ref. [107J]. The characteristics of transition boiling and thermal oscillations in an upflow channel are the subject of Ref. [119J], a semi-empirical model for transition boiling is proposed in Ref. [112J], while different heating methods for studying transition boiling with temperature-controlled test sections are described in Ref. [111J]. Thermal transport rates during quenching were studied by several investigators, who addressed film boiling in saturated drops impinging on a heated surface in Ref. [113J], reflooding of an annular channel in [89J], and the development of quenched metal parts in Ref. [123J]. [88J] uses the results of a numerical analysis to develop an improved correlation for heat transfer in subcooled film boiling to a sphere.

CHANGE OF PHASE—CONDENSATION

Papers on condensation during 1994 were separated into those which dealt with surface geometry effects, those on the effects of global geometry and thermal boundary conditions, papers presenting techniques for modeling and analysis, papers on free-surface condensation, and papers dealing with binary mixtures.

Surface geometry and material effects

One paper of this category showed the benefits of a fillet at the fin-root area of integral-fin tubes [3JJ], another discussed the effectiveness of a composite copper/graphite fluoride plating surface [2JJ], while a third demonstrated the effect of ion implantation on condensation [4JJ]. The final paper in this category presented a theory for the rewetting of smooth and grooved plates [1JJ].

Global geometry and thermal boundary condition effects

Geometric effects continue to dominate condensation papers. Geometries range from horizontal tubes [13JJ, 6JJ] and ducts [12JJ], to finned tubes [17JJ, 10JJ, 5JJ], fluted tubes [7JJ, 15JJ], inclined tubes [9JJ] and vertical pipes [16JJ]. Other geometries studied include vertical plates [18JJ] and horizontal plates [11JJ]. Geometries that are more application-specific are those of air–water heat exchangers [14JJ], concentric cylinder heat exchangers [8JJ], and the production of fibers by the air-gap, wet-spinning process [19JJ].

Modeling and analysis techniques

Papers which seemed to focus on analysis techniques include one which dealt with the interphase mass and momentum transport [27JJ], one with mass transfer effects on the Kelvin–Helmholtz instability [21JJ] and one that presented a boundary layer analysis of inclined condensate flows [24JJ]. Others focus on conjugate effects [22JJ], non-condensable gas effects [28JJ], and the analysis of closed thermosyphons [23JJ]. With design choices in mind, one group of authors presented a sensitivity analysis of correlations for steam surface condensers [30JJ], another compared the basis for safety code assessment of steam generator U-tubes [25JJ], while another presented scale-up analysis techniques for steam drying [26JJ]. Two analyses dealt with processes involving free condensation, one in sulfur recovery [29JJ] and another in the making of steel [20JJ].

Free surface condensation

Papers on condensation which is free of solid surfaces included one which dealt with condensation of aqueous vapor on aqueous solution surfaces [34JJ] while another investigated jet-mixing in a thermally stratified tank [33JJ]. The general analysis of droplet growth in a continuum regime was presented [32JJ] as was the condensation of steam in water [35JJ] and water vapor on chilled brine [31JJ]. One analysis dealt with two-phase flashing flow [39JJ] while another discussed steam injection for sterilization of biological media [37JJ] and a third focused on hygroscopic aerosol behavior in a reactor containment [36JJ]. An aerodynamic study on non-adiabatic transonic flow required addressing condensation effects [40JJ] while another addressed condensation in shock tube flow [38JJ]. Finally, the formation of aluminum aerosol around an evaporating metal drop was analyzed [41JJ].

Binary mixtures

Several papers were on binary mixtures. One addressed special concerns in forced convection [43JJ], another was on gravity-controlled condensation [42JJ], and a third was with non-eutectic vapors of binary immiscible liquids [44JJ].

CHANGE OF PHASE—FREEZING AND MELTING

In this section analytical/numerical and experimental work in the area of phase change, specifically freezing and melting processes are reviewed. There are five subsections in this section: melting and freezing of spheres, cylinders and slabs; Stefan problems; ice formation in porous materials; contact melting; and solidification during casting. Each of these subsections will be further divided into subtopics.

Melting and freezing of spheres, cylinders and slabs

In this subsection melting and freezing in geometries such as spheres, cylinders, slabs and tube banks is reviewed. Several studies were conducted to experimentally and theoretically investigate freezing and melting in cylindrical systems. The experimental studies investigated ice cylinder melting in warm air flow Ref. [1JM]. The numerical and analytical work was pursued by Refs [5JM] and [7JM]. Numerical and analytical studies include an investigation of frost protection around cylindrical PVC water mains [7JM], and melting in a solid showing a melt bifurcation phenomenon [5JM]. A numerical and analytical study of melting in a rectangular geometry was conducted by Ref. [3JM] as well as a numerical study of melting in a rectangular phase-change material [2JM]. In addition, experimental studies of ice formation around tube banks [4JM] and laminar freezing of liquids in convectively cooled tubes [6JM] were performed.

Stefan problems

In this subsection, several studies solved variations of the exact Stefan problem for phase change. The analytical studies included an exact solution of solid/liquid phase change with a convective boundary condition [10JM]; a model using an equivalent volumetric enthalpy variation in non-linear phase change processes [9JM]; and a numerical study of electromagnetic melting and evaporation of spherical metal particles [8JM] were also performed.

Ice formation in porous materials including soils and foods

A number of studies investigated ice formation in porous materials, including foods, soil, snow, and ice in seawater.

Food

A number of papers presented perform experimental measurements, as well as numerical and analytical prediction, of freezing in food and food substitute systems. Experimental studies measured freezing time of food materials [20JM], [15JM] and [22JM], while others included mathematical models of freezing meat balls in belt freezers [22JM], freezing in plate freezers [23JM], in food substitutes [19JM] and others [21JM]. In addition, one study investigated microwave thawing of food materials [24JM].

Soil, snow and seawater ice

Freezing has been examined in soils, snow and seawater. In soils, a study focusing on frost heave [18JM] and a numerical and experimental study addressing freezing in saturated sand [17JM] were presented. The melting of snow has been investigated by a model incorporating the species equation to predict pollution run-off [11JM]; while heat and mass transfer during metamorphism in idealized dry snow was predicted by a 3D model in Ref. [14JM]. Flow visualization was presented for sea ice formation [13JM] and a novel radar technique was used for measurement on the open ocean [12JM].

Miscellaneous

One study investigates phase change in model materials with mushy regions [16JM].

Contact melting

In the area of contact melting several subtopics were identified: melting and melt flows; powders, films and emulsions; crucible melts; glass melting and formation; welding; melts in enclosures; melting in nuclear reactors (fuel and other); and melting in energy storage.

Melting and melt flows

In this subsection, experimental and numerical/analytical activity in melting and melt flows is discussed. Melting studies investigated contact melting in parallel plates [56JM] and horizontal cylindrical capsules [65JM]. The molten zone of the melt was modeled by Ref. [31JM]. Melting of phase change materials (PCMs) flowing turbulently in tubes was investigated and [43JM], provided a numerical study, coupling wall conduction with natural convection melting of a PCM. Laser melting was also investigated in a melt pool [57JM], as well as in superconducting ceramics [48JM] and HgCdTe [67JM]. A finite element study was completed on the role of convection in laser surface melting [63JM]. In addition, melt flow studies were performed for liquid metal flow visualization at solid–liquid interfaces [58JM], and continuous slag removal from an iron melt [73JM]. A novel numerical technique, including a time space method for multidimensional melting and solidification, was also presented [66JM].

Powders, films, emulsions and particles in a melt

The studies which investigated melting in emulsions were presented in coatings [36JM], calcium carbide powder injection into hot metal [80JM, 81JM], desulfurization of iron melt by powder injection [62JM], laser heating of gold films [59JM], and melting during copper nanocluster deposition [32JM].

Crucible melts

Work in the area of crucible melts included studies on the influence of crucible rotation and horizontal magnetic field on dopant concentration in a Czochralski Melt [55JM], spoke patterns that form in a Czochralski Silicon Semiconductor melt system [77JM], and a numerical study of the three-dimensional melt convection during Czochralski crystal growth [54JM].

Glass melting and formation

Studies of glass melting and formation provided analyses of the glass furnace as well as glass formation within it. Glass furnace work included the effects of the electric boost technique [27JM], measurement of temperature in the exhaust gases [30JM], as well as modeling of temperatures in the combustion space in the furnace [75JM]. Glass furnaces with Oxy-Jet burner and fuel technology were analyzed and optimized with computational fluid dynamics techniques [76JM] and their performance analyzed in the production of art glass [61JM]. The particulars of glass formation are discussed in a review of the process and models [50JM], and a review of 3D modeling of glass melts [72JM]. Studies were presented on sand grain dissolution in an industrial glass melting tank [25JM], rheological properties of the glass melt [29JM], numerical models of heat transfer with phase change in silica, glass and ceramic [70JM], and molten glass flows [35JM].

Welding

In the area of welding, a number of analyses were conducted to predict heat and mass transfer within the melt in weld pools [78JM], in keyholes during deep-penetration welding [34JM] and during the application of high electromagnetic fields [69JM]. A number of arc welding studies addressed the effect of flux coating on stability of electrode heating [28JM], the control of the weld temperature of the DC arc furnaces [71JM], the temperature distribution in the cathode [26JM], and the effects of electrode extension on gas metal arc welding [60JM]. Other weld studies explored issues in electrofusion joint welding [51JM] and provided results for a numerical study of the spot welding process [45JM].

Enclosures

Studies on melts in enclosures were investigated by simulation of moving phase change boundaries where the enclosure walls had cyclically varying boundary conditions [42JM], melting in a parallelepiped cavity filled with phase change material [53JM], and wall conduction effects on aluminum melting in a heated enclosure [79JM].

Nuclear reactors

Safety issues related to melting in nuclear reactor cores and fuels was investigated by a number of studies. These included analyses of melting of fuel in light water reactors [52JM], avoidance of melting temperature of nuclear fuel [44JM, 49JM], core melt analysis [68JM], melting of concrete by overlying hot liquid pool [39JM], and the measurement of the melting temperature and the heat capacity of uranium dioxide [64JM].

Energy storage

Melting as a method to store and release energy was examined by a 2D phase change model and compared to experiment [46JM]. In addition, energy storage was studied in several experiments using palmitic acid [40JM] and stearic acid [41JM].

Miscellaneous

Phase change in polyesters during polymerization and annealing [74JM] and melting [47JM] was also studied.

Solidification during casting

In this subsection studies of: mushy region solidification; metal solidification; crystal growth from a melt; and splat cooling are presented.

Mushy zone—dendritic growth

Solidification was studied in a binary NH4Cl-H20 system [112JM], the mushy region of binary liquid metal melts [97JM] and in binary mixtures with active Soret effect [103JM]. Prediction of solute trapping at high solidification rates in binary alloys [89JM] and the shape of eutectic grains in a solidifying alloy [114JM] were also studied.

Metal solidification

The solidification of metals during spinning was examined in dilute Zn alloys [82JM] and copper [122JM]. Laser welds [96JM], weld solidification cracking [94JM] and solidification of aluminum melt [100JM] were also investigated. Solidification of gas atomized metal droplets was studied in rapid solidification of gas-atomized Al-8% Fe droplets [105JM], atomization and deposition of Ni_3Al [111JM], and in gas-atomized alloy droplets during spray forming [109JM]. Solidification of liquid metal droplets impacting on solid surfaces was studied by [101JM] and solidification of metal spray to form a metal deposit was investigated by [95JM].

Crystal growth from melt

Investigations of the growth of crystals from the melt included a numerical simulation of the interface shape and location of tube crystals of $NaNO_3$ and Silicon [107JM], growth of $NaNO_3$ crystals in a transparent furnace [108JM], eutectic inorganic crystallization [123JM], growth of laser oxides in a vertical Bridgman configuration [113JM], dendrite growth at non-isothermal steady state [90JM], crystallization zoning in magnetic bodies [84JM], and extrinsic effects on cellular arrays in the melt [88JM]. A travelling heater method for growth of [Hg,Cd]Te [117JM] and convective transport and interface kinetics in liquid phase epitaxy [106JM] were also studied. In addition, growth rates of Chokhral'skij crystals were investigated in silicon using a thermal-capillary model [124JM], and in yttrium aluminum garnet and gadolinium gallium garnet [119JM].

Casting

Casting was investigated in a number of systems including: squeeze casting of Al-Si alloy [86JM]; electromagnetic field augmentation in a mold [116JM]; squeeze infiltration casting of metal matrix composites [121JM]; centrifugal casting of metal matrix composites containing graphite particles [102JM]; twin roll continuous casting [98JM]; and in rotating plastic molding [120JM].

Splat cooling

Splat cooling was investigated in metal alloys by theory and experiment [104JM] and by quench cooling heat transfer analysis [87JM].

Miscellaneous

Several other studies were conducted in solidification including a 3D numerical FEM solidification model which included effects of magnetic field and reduced gravity effects [92JM], solidification of a dielectric fluid with charged particles in electric fields and reduced gravity [93JM], laser quenching [85JM] and sintering of polymers [99JM]. Other studies investigated the dynamics of crystal growth during frost formation on a horizontal plate [115JM], solidification near tri-junctions [83JM], solidification phenomena in volcanic magma flow [110JM], combination polymerization and crystallization in continuous apparatus [91JM] and formation of large composite parts by injection molding [118JM].

RADIATIVE HEAT TRANSFER

Papers describing the development and application of computational models continue to dominate the radiative heat transfer literature. The subcategories below review papers which focus on the impacts of radiation; papers focusing on the numerical methods themselves are reviewed in the numerical methods section under the subcategory of radiation.

Influence of geometry

View factors continue to be of interest, and various common geometries and applications were discussed by Refs [1K 2K, 4K, 5K, 6K]. Reference [3K] describes the importance of window and sensor geometry in heat-seeking (infrared) missile guidance systems. Papers discussing enclosures and processing chambers are referenced below in the section on radiation combined with convection or conduction.

Participating media

Papers in this category can be further subdivided into those in which gaseous emission and absorption play a dominant role and those in which scattering is very important. The former include model development and validation for handling the spectroscopic nature of gases such as CO_2, and H_2O [26K, 35K, 31K, 29K, 39K, 49K], and applications to conditions which exist in re-entry bow shocks [13K, 45K, 33K, 34K, 52K, 50K, 20K, 17K, 15K], blast waves [18K], and hot jets [46K, 22K, 8K]. Low temperature systems in which scattering is important include fibrous media [32K, 44K], semi-transparent plastics [53K], tissue diagnostics [21K], planetary atmospheres [54K, 30K, 42K, 40K] and oceans [25K, 38K]. Models for scattering in high temperature systems were reported for fluidized beds [56K, 57K], particle laden flows [41K], a photocatalytic reactor incorporating suspended particles [11K], and of course, plasma and combustion systems. The former are treated in a separate section. For the latter, models of radiative heat transfer are particularly important in studies of sooting flames [48K, 27K, 14K, 28K, 23K, 24K, 55K], solid fuel combustion [43K, 9K, 10K, 7K, 47K], or combustion in low-gravity environments [12K]. The influence of absorbed and emitted radiation on the growth and coagulation dynamics of particles in powder synthesis thermal reactors [16K] and in combustion-driven reactors [37K] was also investigated. Models were also developed for novel combustor geometries [36K] and high-energy rocket propulsion [51K]. Hamins *et al.* reported surface heat flux measurement in pool fires [19K].

Radiation combined with convection, conduction, or mass transfer

The interactions between radiative, convective or conductive fluxes in various geometries was demonstrated in many investigations, including basic investigations of heat transfer modes in enclosures [59K, 60K, 61K, 106K, 89K] as well as applied investigations of glass furnaces [98K, 79K], crystal growth [86K, 88K, 95K], semiconductor wafer processing systems [58K, 64K, 84K, 82K, 75K], boilers [81K, 77K], packed/fluidized beds [101K, 80K, 87K, 90K, 104K], dilute two-phase flows [73K], hot fluids in pipes [74K, 99K, 65K], and current flow in electrical power cables [72K]. Somewhat related are discussions of applications in building heating [76K, 105K] and insulation [68K, 70K]. Applications involving bulk materials included a discussion of the effectiveness of combined hypothermia/radiotherapy cancer therapy [92K] and a set of paper regarding the cooling of various fruits [66K, 67K]. Combined heat transfer modes in planar and layered geometries with various boundary conditions are encountered in a number of widely varying applications, including gaseous layers [94K, 97K], laminated composites [103K, 93K, 102K, 100K], window heating during fires [78K], and atmospheric exchange with canopy and ground covers [91K]. Materials processing applications involving infrared drying or curing of paper [85K], textiles [62K], thermoset-impregnated hoop wire tows [63K] various paints and coatings [69K], and even gelatinous materials [71K] were also described. Other processing applications employing radiation in other parts of the electromagnetic spectrum included an analysis of the deformation of electron beam shadow masks [83K] and a fundamental investigation of microwave heating of a semi-infinite material with temperature-dependent properties [96K].

Intensely irradiated materials

This category is really a subset of the preceding one, but the maturing of pulsed laser technology continues to spark a relatively large number of new applications. The properties and temperature distributions of single- and multi-layer films heated by pulsed lasers are the subject of papers by Refs [111K, 112K, 113K, 107K]. Effects of materials properties on laser-produced plasmas and laser processing applications were also discussed by Refs [110K, 109K, 114K], including a discussion of laser ablation-driven inertial fusion [108K]. Some related papers can also be found in the section on Conduction.

Experimental methods and properties

Custom-designed emissometers and reflectometers were used to measure the emittance and reflectance of various materials in [127K, 124K]. [117K] described a portable infrared photometer for monitoring near-infrared absorption to determine trace concentrations of greenhouse gases, while [120K] reported the infrared absorption spectra of lime–aluminosicilicate glasses. Probes useful for measuring temperatures in fluidized beds [122K] and heat transfer coefficients in furnaces [128K] were also described and characterized. The transient response characteristics of high temperature superconductor films, whose potential for bolometer applications may be of particular interest to readers of this section, were discussed and measured by [125K, 130K, 133K, 115K, 116K]. Properties of organic and thermal coatings were discussed by [126K, 118K, 132K, 123K]. The influence of surface finishes and geometry on emittance and reflectance properties were described [129K, 131K], as was the interpretation of surface reflectances from remote sensing data [121K, 119K].

Miscellaneous

This year, only a single paper did not fit well into any of the above categories, and yet it discusses and interesting phenomena: Arisudan *et al.* [134K] described a weak interaction between gasdynamic and radiative fields which can produce weak discontinuities in the gaseous field.

NUMERICAL METHODS

A significant amount of research continues in the area of numerical methods. New procedures and algorithms are developed for solving the partial differential equations that describe the processes of heat transfer and fluid flow. The numerical methods are also applied to a wide variety of physical 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 referenced in this section.

Conduction

Various aspects of the finite element technique applied to heat conduction are described in a number of papers. These include: the transient behaviour [1N], adaptive techniques [9N, 5N], hyperbolic nature [2N], stability [3N] and heat sources [11N]. The random-walk algorithm is developed in Ref. [7N]. The strongly implicit procedure is presented in a vectorized form [8N]. A new explicit finite volume procedure has been described [10N]. Special applications of a diffusion model are given in Refs [4N, 6N].

Phase change

Solidification problems have been addressed with a variety of numerical methods. Methods dealing with solid–liquid phase change have been presented in Refs [12N, 13N, 14N, 15N, 18N, 19N, 20N, 21N]. The phase change in injection molding is addressed in Ref. [16N]. Reference [17N] deals with moving heat sources in phase change.

Convection and diffusion

The upwind method for convection and diffusion in natural and forced convection is examined [27N]. The effect of grid orthogonality on the solution accuracy is investigated [24N]. The boundary element method is used for solving the convection–diffusion equation [22N, 23N, 26N]. Reference [28N] studies the interaction between conjugate heat transfer and the convection-diffusion process. The formulation of the outflow boundary condition with wall conduction is presented [25N].

Radiation

Radiation in absorbing-scattering media is handled by different variants of the discrete ordinates method. Such methods are presented in Refs [31N, 32N, 33N, 34N, 36N, 39N, 37N]. Transient and multidimensional aspects are treated in [40N, 42N]. The zone method is used in Refs [41N] and is combined with the Monte Carlo method in [38N]. The MacCormack scheme is considered with radiation [29N]. Reference [30N] describes a collapsed-dimension method for radiation. An adaptive finite-element method is used for radiation in [35N].

Solution of flow equations

As a part of the calculation of convective heat transfer, it is necessary to compute the fluid flow. Calculation methods for solving the flow equations are published extensively; here the work that is mainly relevant to heat transfer is reviewed. Various aspects of the finite-volume method are presented in Refs [64N, 65N, 67N, 69N]. Finite-element methods for flow problems are discussed in Refs [43N, 54N, 66N, 56N, 61N, 62N]. References [52N, 55N, 58N] deal with the use of unstructured grids for flow computation. Segregated soliton methods for the momentum and continuity equations are developed in Refs [44N, 47N, 68N]. References [46N, 53N] focus on the non-orthogonal terms that arise in the use of general curvilinear coordinates. The choice between staggered and nonstaggered grids for regular and monorthogonal grids is addressed in Refs [48N, 49N]. A multigrid procedure for flow problems is described in Ref. [63N]. References [45N, 50N] deal with flows with free surfaces. Methods for multiphase flows are developed in Refs [51N, 57N, 59N, 60N].

Other studies

Adaptive techniques for heat transfer and fluid flow are presented in Refs [70N, 75N]. Benchmark results for computational heat and fluid flow are generated in Ref. [71N], while some challenges to the thermal-hydraulic codes are presented in Ref. [72N]. The stability and other properties of numerical methods in RELAP5/MOD3 are discussed in Ref. [77N]. Reference [73N] deals with computer modeling of shell and tube heat exchangers. Numerical modeling of nucleate boiling is addressed in Ref. [74N] and numerical calculation of droplet evaporation is performed in Ref. [76N].

TRANSPORT PROPERTIES

Thermal conductivity and thermal diffusivity

Novel processes and devices utilizing special materials, whose thermal conductivity values must be known, is the common theme. The thermal conductivities of 14 silicate esters are determined. New empirical equations involving easily measurable ultrasonic parameters are proposed and compared with experimental thermal conductivity values [1P]. The thermal conductivities and heat capacities of water-surfactant-18-crown-6 ether systems are measured at 25°C [2P]. For thin films, of GaAs/AlGaAs, a new experimental technique yields thermal diffusivities in both parallel and perpendicular directions using a laser source to heat the sample and a fast response temperature sensor to pick up the thermal response. The phase delay between source and sensor allows the directional diffusivity to be found [3P]. An assessment of various expressions for the apparent thermal conductivity of cellular materials is performed, and dependencies on material parameters are presented graphically. Predicted results are compared with measured values for a wide range of materials [4P]. Transient heat transfer from cylindrical specimens to water and air allows conductivity, diffusivity and specific heat to be determined in addition to cooling process parameters [5P]. For semi-transparent glass a useful distinction is made between the "active" thermal conductivity, which applies when the temperature distribution in the glass volume is sought and the "passive" form which applies when heat transfer occurs through long-range photons, most of which are both emitted and absorbed outside the glass volume. The sum of the two is the apparent thermal conductivity which indicates the overall heat flux through the glass [6P]. A mixture theory based on ensemble-averaging is proposed for studying the thermal behavior of heterogeneous media and tested for a two component medium [7P]. Thermal condition in amorphous dielectric layers affects the performance of electronic circuits. The influence of boundary scattering on the effective thermal conductivity for conduction normal to amorphous silicon dioxide layers is analyzed and found not important at room temperature [8P]. Thermal diffusivities of doped UO_2 and (U, Gd)O_2 pellets were measured by a laser flash method and their thermal conductivities were evaluated [9P]. An empirical relationship is determined to provide estimates of matrix thermal conductivities of quartz, calcite and feldspar crystals based on dry state properties [10P]. The thermal conductivity and thermal diffusivity of pressed-powder specimens of cyclotrimethylenetetranitramine are measured for specimen temperatures ranging approximately between −20 and 50°C [11P]. A transient, automated technique measures the thermal conductivity of unconsolidated powders (e.g. powdered iron) from room temperature to 800 K in various void-filling gases at variable pressures [12P]. Thermal conduction temperature dependencies in $Sn_2P_2S_6$ and $Pb_2P_2Se_6$ crystals have been studied [13P]. A new method, based on the Joule effect, is used to determine the thermal conductivity of pellets of seven different propellants and explosives [14P]. The influence of Kapitza thermal resistance of Cu-epoxide resin is studied at cryogenic temperatures. A numerical model is developed for calculating the effective thermal conductivity coefficient of this composite material, and experimental investigations have been performed at superfluid helium temperatures [15P].

Thermodynamic data

Critical temperatures and densities are determined by observation of meniscus disappearance for liquid vapor coexistence regime of seven alternative refrigerants: HFC-32, HCFC-123, HFC-125, HFC-134, HFC-134a, HCFC-142b and HFC-152a [17P]. Heat capacity measurements are investigated as a means of understanding ac calorimetry [16P] and [18P] to provide data on the ternary system water + sodium dodecylsulfate + NaCl. The phase and aggregation behavior of aqueous poly(oxyethylene)-poly(oxypropylene)-poly(oxyethylene) triblock copolymers has been studied [19P].

HEAT TRANSFER APPLICATIONS—HEAT EXCHANGERS AND HEAT PIPES

Thermosyphons

Continuing activity marks the sustained interest in the design, analysis, fabrication, operation and maintenance of heat exchangers across a wide spectrum of applications.

Heat exchangers

Mathematical models are used in a number of papers to predict and optimize heat exchanger network performance [7Q, 11Q, 12Q]. Other analytical approaches seek solutions to the parallel flow, three-fluid heat exchanger problem [15Q], use the "lumping" of the heat exchanger as model [4Q], and assess the importance of "secondary losses" in a practical air-cooled condenser unit [6Q]. The cooling potential of earth-to-air heat exchangers is examined [8Q] and the finite element method is applied to the performance of concentric-tube heat exchangers [5Q].

Experimental investigations explore the influence of baffle/shell leakage flow on baffled shell-and-tube exchanger performance [14Q], utilize a temperature oscillation technique to evaluate thermal parameters [13Q], consider gas–solid cross-flows with low solids concentration [10Q] and aim to further understand fully developed turbulent flow in rod bundle subchannels through power spectral measurements [19Q]. Analytical modeling of transient flows in evaporating flow systems is also considered [17Q].

At low temperatures the following are worth noting: The role of the plate heat exchanger in refrigeration [2Q], the use of welded plate with refrigerants [3Q], an analytical model for regenerative refrigerators [18Q], maldistribution of air flow on performance of a compact R134a evaporator [16Q], and pulse tube cryocooler performance [9Q, 1Q].

Design

Non-metallic heat exchangers are the focus of a number of papers. Where heat transfer, rather than transmission is the goal, plastics based exchangers are an alternative [21Q, 22Q]. Polymer films [24Q] and flow passages in graphite blocks [23Q] distinguish other approaches. Other design considerations examine the relationship between the economic and entropy optimum heat transfer rates [20Q]: the thermal performance of various baffle types [25Q]; the 25 year effort to develop an all welded, stainless steel, compact heat exchanger [26Q]; and the historical perspective on the regenerative heat exchanger proposed by Stirling's version of a closed-cycle hot air engine [27Q].

Direct contact exchangers

Such exchangers range from electronic component coolers to cooling towers and air washers. Using mist cooling, an experiment studies droplet behavior in water droplet–air mist flow and heat transfer characteristics at the heated surface [30Q]. In other works a computer model simulates direct contact, condensing heat exchangers for gas furnaces [28Q] and another model an air washer facilitating the comparison of proposed air conditioning systems [29Q]. Cooling tower selection in process industries [32Q] and scraped surface heat exchangers used in the food industry [31Q] are examined.

Enhancement

A variety of techniques are examined for enhancing heat transfer: segmented baffles compared to helical baffles [43Q], electrostatic effects (or electrohydrodynamic-EHD) [42Q], vortex generators [36Q, 34Q], spiral exchangers [33Q], and external, rectangular, axial extended surfaces with interruptions [44Q]. For crossflow heat exchangers the efficacy of strip-type inserts is studied experimentally [38Q]. Also for crossflow with suspended particulates, a two part study examines the heat transfer mechanism and experimentally determines the effect of solid particles on heat transfer for the first tube row [40Q, 41Q]. Other papers report on compact heat exchangers for desalination distillation [39Q], micro exchangers fabricated by diamond machining [37Q], augmentation of heat transfer in evaporators and condensers used in refrigeration, air-conditioning and heat pump systems [45Q], and in cooling towers being repaired or modified [35Q].

Fouling/deposits/surface effects

The prevention of fouling is the focus of a number of papers. Many of these center on the operation and performance of flash evaporators in desalination plants and the effectiveness of various additives [46Q, 47Q, 48Q, 52Q]. Another study investigated the dynamics of surface fouling and heat transfer coefficient variation [49Q]. Three types of inserted spring elements are used for on-line cleaning of fouled surfaces and their performance assessed [55Q]. A number of papers treat heat exchanger fouling from a particular viewpoint: Dairy industry [51Q, 56Q], furnace operation [54Q], coke-oven gas-cooking system [53Q] and power plant [50Q].

Reactors—chemical/nuclear

Several papers consider the heat transfer aspects of reactors. These include an examination of the "blow out" temperature by heat and mass analysis [61Q], the development of criteria for mass transfer limitation [59Q], heat exchange influence on the efficiency of hydrocarbon-steam and CO conversion [58Q], the exceptional performance of a heat exchanger preheater in a novel, short contact time batch reactor [60Q], heat exchanger monitoring in chemical processing [57Q], heat exchanger operating efficiency in the near-critical region [62Q], and the use of decay heat exchangers in the advanced pool-type liquid metal cooled reactor [63Q].

Thermosyphons (heat pipes)

Activity continues to mark this area of applied heat transfer. The foci of this extended effort are several: The advantage of a binary-mixture working fluid for the control of electrical devices [71Q], the analysis and experimental results for the steady-state performance of the gravity-assisted, two-phase, closed thermosyphon [82Q], limiting heat fluxes in horizontal and slightly inclined devices [64Q], effects of transverse vibration on the capillary limit [67Q], performance of a rectangular, double loop, natural circulation system [68Q], proposal of the mechanism of operation of an inverse circulating thermosyphon evaporator [80Q], and an attempt to hydrodynamically simulate the entrainment phenomena of a heat pipe system [73Q].

Analytically the following efforts are noted: two-dimensional transient model for simulating operations of fully-thawed heat pipes [81Q], the mechanics of operation of a novel, inverse circulating thermosyphon evaporator, general operation and performance viewed from fundamental thermodynamics [79Q], the entrainment process in two-phase parallel flow and wave instability theory [74Q], heat and mass transfer during evaporation in a wet capillary structure and heated wall [69Q], and the use of two implicit solution methods for modeling vapor flow in a heat pipe (said to be 100 times faster than an explicit solution method) [65Q].

Applications and special aspects of heat pipe operations include a number of inquiries: Two-phase devices for cooling high-power multichip modules [75Q], the practicality of using a heat-pipe installed in a milling machine spindle to remove frictional heating in spindle bearings [70Q], a gas-to-gas heat pipe exchanger family for food processing [77Q], the startup performance of a liquid metal device in near-vacuum and gas-load modes [78Q], and a scheme for recovering waste heat from gas turbine engine stacks [76Q]. Miniature and micro heat-pipes are reviewed, including their design and operating limits [66Q] and a detailed mathematical model developed to examine the heat and mass transfer process in such devices [72Q].

HEAT TRANSFER APPLICATIONS—GENERAL

Aerospace

An attempt is made to develop a multidisciplinary, computational methodology to predict hot-gas-side and coolant side heat transfer in film cooling of liquid rocket combustors [7S]. Navier–Stokes and direct Monte Carlo calculations for flow near the continuum limit with slip boundary conditions are compared [5S]. The evaluation of thermal radiation emitted from shock waves in real air by Monte Carlo methods is discussed [2S]. A paper [6S] predicts the aero-optic performance of hypersonic interceptors. The trajectory and configuration of a vehicle to Mars is optimized [8S]. The thermal design of INSAT-2A is achieved [4S] by passive thermal control techniques. Flow and forced convection analysis determine [1S] solar heat effects on space shuttle launch components in extremely hot conditions. The model for recombination of oxygen on a silicon-dioxide surface is reviewed [3S].

Bioengineering

Heat transfer is considered [11S] within a perfused tissue in a vessel. The ability of Pennes' bioheat equation and the effective thermal conductivity equation to predict in vivo temperature files are compared [12S]. The Weinbaum–Fiji equation can be applied to predict [15S] situations where heated thermistors are placed in the kidney cortex. A small artery model (SAM) for thermistor measurements of perfusion in a canine kidney is developed [9S] as were finite element heat transfer models for thermoseeds and catheters to simulate ferromagnetic hyperthermia [13S]. A multiple layer finite element analysis predicts [14S] skin temperatures and times for second and third degree burns in flash fires. A mathematical procedure is described [10S] which predicts lethality in a sterilization system for foods.

Digital data processing

Models for electro thermal network simulation [18S] are developed. Heat transfer during wire bonding is discussed in [19S]. A computational fluid dynamics tool is used [20S] to evaluate velocity and temperature of air flow in computer systems enclosures. The proximity gap between the hot plate and the water dominates the heat transfer in a coated silicon wafer [16S]. The dependence of flash temperature [17S] on tape speed and other operating parameters was studied. A new air cooling scheme [24S] consisting of converging, impinging, and diverging flows was proposed for 3-D packaging. Hot spot temperatures of electronic modules can be reduced [21S] by increasing the fin thickness and height in flow direction. New chips generate five times the heat of todays CPU [23S]. This can be rectified by integral immersion cooling of multichip module packages [22S].

Energy

The basic needs of knowledge in convective heat transfer [48S] are outlined as perceived by industry. Cooling problems in gas turbines have been widely studied, such as: vanes and first stage blades of space shuttle fuel-side turbines [29S], ability to measure and compute unsteady heat flux in turbine blades [37S], convection at entrance region of cooling holes [34S], thin liquid films in various applications [26S], prediction of transition [35S], wake induced unsteady heat transfer [46S], exhaust gases to water or ammonia–water mixture [41S], a new design for first stage vanes [50S]; and grid-generated mainstream turbulence [49S]. No significant difference was found in off-design performance of thermal efficiency of single or two-shaft gas turbines [38S].

Spark ignition and flame initiation was studied for piston engines in a number of papers. A detailed chemical reaction scheme [40S] was employed. Diesel combustion was studied [39S]. Heat losses in the engine head [42S] and during knocking in a four-stroke gasoline engine [30S] were measured.

Heat transfer in the riser tubes of high-temperature gas cooled reactors could be measured [31S]. A computer model was developed [54S] for the study of severe accidents. Pebble bed core reactors were computed for cylindrical and other shapes [28S]. A nonlinear analysis is presented for thermal fronts in the edge and scrape-off layer of Tokamacs [36S]. The stability of internally-cooled super conductors in cables [53S] is analyzed with results agreeing with experimental ones.

Cryostats for MHD propulsion ships have supports transmitting electro-magnetic force from superconducting coils to the vessel. The thermal and mechanical properties of those are described [45S]. Cooling characteristics are described [43S]. The paper [33S] describes the heat transfer in high power density magnets. A metal hydride energy system [32S] employs a numerical model. An experimental rig simulates heat transfer in a phosphoric acid fuelled cell stack [25S]. Heat transfer models simulate incineration of municipal waste [47S, 51S].

The sources of heat are discussed for aluminum/air batteries [52S]. An analysis studies heat transfer in electrical transformers immersed in oil [27S]. The stability of a cable-in-conduit conductor is high [44S] when operated below a limiting current.

Environment

A paper [57S] describes a simplified thermal model of buildings validated by measurements on 32 buildings. Heat and mass transfer in a grain silo was studied analytically and experimentally [55S]. A prediction of underground temperature was attempted for the planned Gotthard railroad tunnel [59S] with an estimated error of 5–10°C. A heat exchange experiment on a steel tube immersed in the ground provided data [58S] for the use of soil as a heat sink. Cycle and heat transfer analysis supported by experiments demonstrates the advantages of using mixtures of R22/R142b in heat pumps [56S].

Manufacturing

A large number of papers are concerned with casting using numerical modeling technology to improve quality [78S], to simulate continuous casting [81S], to analyze heat transfer and solidification [63S, 66S]. Thermal and optical properties were measured [82S]. Multiphased flow was analyzed [85S] for casting of steel slabs [60S] and the results verified by measurements [75S]. The roll casting process was improved by steady modeling [77S]. An analytic method predicts normal stresses in a die mold [68S]. Flow, heat transfer, and separation is analyzed in continuous casting tundishes [83S] and the effect of flow modifier [73S]. Heat transfer optimization decreased cracking in steel casting [72S].

Experiments on cooling of rolls have been summarized [80S]. Enthalpy and energy balances are compared [69S] for heating of steel slabs. Coupling of heat transfer and thermomechanical problems in partially solidified material has the potential of instability [87S] with the Stefan number being a parameter. Heat transfer to continuously moving material in hot rolling, fiber drawing, extrusion, crystal growing—was investigated experimentally [71S]. An advanced annealing cooling cover accelerates cooling [84S] without use of water. Flow, heat transfer and thermophoretic transport for vapor deposition equations were solved numerically [86S].

Three heat transfer regimes were identified during laser welding, based on analytical model predictions of metal composites [76S]. A fuzzy control method is proposed for arc welding by regulation of the surface temperature [62S]. The life time of the tool is one of the most decisive factors for economic evaluation of precision forging [65S]. An analytic model predicts the tool temperature field in metal cutting [79S]. A one-phase fluid model describes flow and temperature field between electrodes in electro chemical drilling [70S]. The migration of macromolecules during flow of an initially homogeneous polymer solution is reviewed [61S]. A boundary element solution of the heat transfer during polymer processing is presented [64S]. An IR imaging system to measure thermal diffusivity of polymer samples is described [67S]. A heat transfer analysis determines the time required for crack healing in amorphous polymers [74S].

Processing

Detailed experiments studied the dynamics of R-11 blown polyurethane foam formation [89S]. The extension process of non-Newtonian fluids (plastics, food material) was numerically modeled [94S] regarding heat and mass transfer. Collinear mirage detection is a simple method for thermal diffusivity measurements of transparent polymer foils [96S].

A wafer temperature control system was developed for thermal processing of semiconductor equipment [100S]. The advantage of desorption with internal sorbent heating was proven [98S]. Conjugate heat transfer and particle deposition in a chemical vapor deposition process including thermophoretic transport was analyzed [97S]. Sapphire fibers for optical sensors and composite structures are manufactured by the EFG process [101S].

Rotating cone reactor [103S, 104S] and stirred tank reactor [90S] are investigated by computations and experiments. A mathematical model of baking is validated experimentally [105S]. A very computational process simulates food sterilization for flowing solid–liquid food mixtures heated by an electric current flowing through the mixture [106S].

A simulation study deals with dryers for biological material [92S] and computes volumetric heat transfer coefficients for rotary dryers [88S]. A new scale-up method for contact dryers is based on the assumption that heat transfer is the controlling mechanism [102S].

A heat transfer model clarifies the steady food grinding process comparing the results with experiments [95S]. Circulating temperature and pressure measurements were made with casing in hole for cementing conditions [91S]. The means to reduce operating costs for cooling and ventilating of deep level mines by 67% are discussed [93S]. Radiation dominates heat transfer in a medium phosphide crystal growth process and makes the system stable and predictable [99S].

SOLAR ENERGY

Reviewed papers include research in passive solar design and energy conservation in buildings as well as active solar thermal technologies and resource assessment. Papers dealing specifically with photovoltaics or wind energy are not included.

Buildings

Solar greenhouses continue to attract attention. Papers include a study of 95 greenhouses around the world [23T], a demonstration project in Europe [22T], design of a ventilation dehumidifier [28T], modeling of controls [12T], heat transfer processes in covers [19T] and earth-to-air exchangers [17T].

Rating the thermal performance of fenestration systems [2T] and heat transfer models of glazings [18T, 30T, 7T, 3T] are presented. Applications in residential buildings include studies of storage walls [26T, 16T, 27T], the effect of air leakage on heat transfer within walls [13T], ventilation of patio dwellings [5T], effect of radiant temperature on comfort control strategies [10T], simplified methods of determining energy loads due to solar gain [4T], development of a thermal comfort index [8T], as well as specific concepts for building or air conditioning design [24T, 11T, 14T, 29T].

Papers dealing with commercial buildings include a description of the 21st Century Tower in Shanghai [25T], a combined passive/active solar building at Stuttgart University [9T], control strategy for ventilation systems [15T], and a proposed index to rate performance of HVAC systems [21T]. Efforts continue to simplify and refine simulations of energy performance of buildings [1T, 6T, 20T].

Non-concentrating collectors

Work on flat-plate collectors includes studies of flow and heat transfer in air collectors [32T, 39T] and in liquid collectors [33T, 38T, 35T]. Operating characteristics of liquid integral–collector–storage systems [36T], evacuated tube collectors [31T] are presented. Use of a collector with *n*-pentane as the working fluid is analyzed for water pumping [37T]. A new indoor solar simulator designed to test collectors and water heating systems is described [34T].

Concentrating collectors and systems

Several papers address development and analysis of solar receivers for power production in space [46T, 43T, 57T]. Terrestrial power production using Stirling engines is modeled by [40T, 44T, 53T]. Modeling of parabolic trough collectors includes presentation of a closed-form expression for the intercept factor that eliminates the need for detailed ray-tracing [42T], steam production [47T], the effect of inclination on convective heat transfer [51T], and a method for estimating thermal losses [58T]. A two-year project at Sandia National Laboratories to demonstrate the use of pumps and valves with molten salt is presented [55T]. Other component studies address materials [52T] and geometry [49T] of reflectors, windows and materials for volumetric receivers [45T, 59T], and an adaptive control scheme for a distributed collector field [48T]. To simulate a blackbody solar receiver, [41T] investigated the effect of orientation on natural convection in an horizontal annulus with an open trough. Solar reformation of methane is addressed by Refs [50T, 54T] and [56T].

Radiation characteristics and related effects

The majority of the published work in this area is development of new algorithms or numerical models for generating synthetic radiation data or for interpreting/extrapolating limited meterological data [60T, 67T, 68T, 69T, 70T, 73T, 77T, 79T, 83T, 84T, 85T]. Efforts continue to obtain site specific solar meterological data particularly in the Middle East [62T, 63T, 64T, 66T, 72T, 74T, 75T, 76T, 80T, 81T, 87T]. Comparison of measured and predicted meterological data is used as the basis for evaluating and adjusting existing models [62T, 64T, 71T, 72T, 74T, 87T]. Several papers discuss accuracy and appropriate techniques to measure and analyze meterological conditions [61T, 65T, 86T]. The question of physical and end-use accuracy of satellite-derived irradiance is discussed by Ref. [78T].

Water and space heating

Work in low temperature solar heating is focused primarily on domestic water heating and swimming pool heating. In water heating systems, the desire for simpler systems with fewer mechanical parts and no controls, has resulted in renewed interest in self-pumping [91T] thermosyphon systems [89T, 95T, 96T, 99T, 105T], traditional forced-flow circulation systems that use photovoltaic-powered dc pumps [99T], solar heat pumps [103T] and a method of avoiding freeze failures in direct systems [107T]. A relatively new concept in water heating is a hybrid system that combines solar thermal and photovoltaics. The system is a thermosyphon water heater with PV cells attached to the top surface of the absorber. Experimental observations are compared to modeling efforts [96T]. Rating and certification of water heating systems in the US continues to rely heavily on TRNSYS simulations. [90T] recommends controller settings in these simulations that allow fair comparisons of different systems.

Performance of swimming pool heaters is measured at sites in Switzerland [101T, 102T], Germany [93T] and the US [106T]. [94T] presents a progress report on the success of a manual for building a do-it-yourself copper system. Model development is presented by [88T], [97T] and [98T]. Papers on space heating are limited [92T, 100T, 104T]. The unglazed perforated plate collector analyzed by Ref. [100T] is a promising technology.

Space cooling and refrigeration

Papers in this area describe and evaluate performance of solid [109T, 110T, 116T] and liquid desiccant [111T] systems. Technical and economic performances of open-cycle absorption cooling are modeled [108T] for regions of the US, arid regions [112T], Madrid [114T] and Taiwan [117T]. Solar powered charcoal/methanol refrigerator/ice maker systems are studied by [113T] and [115T].

Stills

Most papers address methods of improving technical performance. Application of a vacuum in a solar still increases the water productivity by 100% according to [119T]. [121T] considers inclination of the cover and its effect on evaporative heat transfer. Productivity of a continuous-flow thin-film design is favorably compared to that of a basin still [118T]. A method of predicting productivity for a given climatic condition and initial condition of seawater is given in terms of a vapor pressure correlation [120T].

Storage

Efforts continue to characterize and control mixing in sensible heat storage vessels [124T, 125T, 133T]. A simulation model of sensible seasonal storage in aquifers is described [130T]. Study of the use of phase change materials includes experimental analysis of the use of stearic acid in a single unit collector/storage vessel [122T], use of palmitic acid [129T], and use of multiple storage vessels with different salts to take advantage of varying collector temperatures [126T]. Models of the phase-change process consider second law analysis [123T], solid–solid transition [127T], a source-sink method for two-dimensional heat transfer analysis [132T], and storage in space station freedom [131T]. Thermochemical storage with $Ca(OH)_2CaO$ pellets is considered by [128T].

Ponds

Studies aimed at characterizing and improving performance of solar ponds are primarily numerical models. Experimental work is principally laboratory scale although performance of a new brine reconcentration system at the University of Illinois half-acre pond is reported [140T]. Other experimental projects investigate operation of a closed-cycle salt-gradient pond [136T] and the effects of halobacteria and selected chemicals [145T] and water turbidity and salt concentration [146T] on transmission of solar radiation. Analytical and modeling efforts consider activity coefficients and vapor pressure of hypersaline solutions like those in the Dead Sea and in Utah [141T], control of double-diffusion stratified layers [139T], instabilities resulting from injection and withdrawal to maintain stratification [138T], limitations of steady-state models [144T], and various models of thermal behavior [134T, 135T, 137T, 142T, 132T].

Cooking and drying

Modeling of box cookers [148T, 149T] and crop dryers [147T, 150T] may lead to improved designs.

Solar chemistry

Interest in photocatlytic detoxification is growing. The effectiveness of various catalysts and reactor designs are investigated. Most studies consider the use of titanium dioxide. Applications include the destruction of 4-chlorophenol [152T, 159T, 160T] nitroglycerine [153T], dicyanomercury and potassium tetracyanomercurate [154T], chlorofluuorocarbons HCFC and HFC [156T], ammonia [157T]. Other papers consider the photocatalytic properties of tungsten oxide on silica gel [158T], hazardous chemical waste treatment in volumetric receivers in a solar furnace [155T], and fuel production via photocatalytic reduction of carbon dioxide [151T].

PLASMA HEAT TRANSFER AND MAGNETOHYDRODYNAMICS

Plasma modeling and diagnostics

The majority of the plasma characterization papers are concerned with fluid dynamic modeling of specific configurations with emphasis on describing turbulence and mass transport by diffusion. In Ref. [2U] a two-dimensional κ–ε model of an induction plasma torch shows presence of laminar and turbulent flow regimes, while in Ref. [9U] the mass transfer by diffusion is described for a similar configuration but with cold gas injection into the plasma. Analytically derived corrections for stagnation pressure measurements with a Pitot tube in a high speed air plasma flow taking into account real gas and compressibility effects are presented in Ref. [8U], although chemical equilibrium is assumed. An experimental study of species concentration profiles in an Ar–He plasma jet issuing into an air environment using an enthalpy probe/mass spectrometer combination has shown effects of entrainment and demixing by diffusion [5U]. Flow and heat flux distributions in high enthalpy nitrogen flows as used for re-entry simulation have been obtained with various diagnostic techniques [4U]. For a MPD thruster configuration, the effect of argon addition on the nitrogen plasma flow has been characterized experimentally [10U] and for a similar configuration, the different contributions to the anode heat flux have been determined as a function of the operating parameters [6U]. Calculations giving electrode heat fluxes for moving arc-electrode attachments are described in Ref. [7U].

Two papers deal with radiation transport models, one using the recently developed method of partial characteristics for describing the emission/absorption properties of SF_6 plasmas [1U] and the other investigating radiative energy transfer in the cathode region of an arc heater [3U].

Plasma—particle interaction

Several papers are concerned with modeling specific effects influencing heat and momentum transfer from a plasma to particles, such as particle charging [14U], surface radiation [11U], and non-sphericity of the particles [13U]. The effect of thermophoretic forces is described in Ref. [12U], and calculations of the motion of particles in a high velocity flame is presented in Ref. [15U].

Laser—plasma interaction

Non-local energy flux models have been used to describe laser produced plasmas [22U, 20U, 21U], describing corrections to classical modeling approaches and including effects of inverse Bremsstrahlung. A model of laser heating of a hydrogen plasma at high power levels showed only small deviations from kinetic equilibrium between the electrons and heavy particles [18U]. A model describing the formation of a plasma due to laser beam interaction with a surface is presented in Ref. [23U], considering two regions, one plasma layer absorbing the laser radiation, the other a cooler vapor layer in front of the metal surface absorbing the plasma radiation.

Time resolved measurements of radiation absorption by laser generated Al plasmas are presented in Ref. [19U] and the experimentally determined effects of the ambient gas and pressure on laser excitation for diagnostic purposes are reported in Refs [16U] and [17U].

Specific plasma applications

Several modeling approaches have been used to describe various aspects of different arc welding processes and in Ref. [27U] a review of several models is presented. Specific modeling approaches published include finite element discretization to describe the moving arc heat source [30U, 24U], a three-dimensional boundary fitted coordinate system for describing the molten metal flow [29U], and an analysis of the keyhole formation in the weld as a function of various parameters [28U]. Results of LDA and pressure probe measurements of the two-phase flow in an underwater welding process are described in Ref. [36U].

Investigations of plasma effects in steelmaking are described in Ref. [33U] with regard to nitrogen pickup by the molten metal due to air entrainment in a plasma tundish heater and in Ref. [31U] with regard to surface hardening due to phase transformations following arc heating. Surface carburization of steel using a combination of pulsed plasma heating and subsequent quenching is described in Refs [35U] and [34U] as an environmentally friendly surface treatment method.

Further specific application oriented studies include heat transfer studies from a plasma jet igniter to liquid methanol droplets in methanol powered engines in cold climates [25U, 26U], and mixing studies of arc plasma produced atomic nitrogen with engine exhaust gas mixtures to reduce NO_x [32U].

Magnetohydrodynamics

Boundary layer models in MHD channels remain an attractive research field, with publications of descriptions of a similarity method involving application of a geometric transformation for describing the boundary layer in a flow over an insulating wall [39U], and of models for the unsteady flow of an incompressible, electrically conducting fluid over a porous plate [42U] and a convex surface [40U]. Calculations of velocity and temperature profiles and heat transfer rates for a MHD radial wall jet are presented in Ref. [45U], and the stability of the cylindrical interface between two magnetic fluids under a periodically varying radial magnetic field is modeled in Ref. [41U]. The effects of Joule heating and viscous dissipation in liquid metal sliding contacts for high current applications is discussed in Ref.[43U].

Measurements of the increase in heat flux from a supersonic, high temperature inert gas flow to the electrodes of a disk MHD generator with increasing magnetic fields are described in Ref. [44U]. An interesting method for characterizing the flow structure in a coal fired MHD flow boundary layer uses line shape measurements of the potassium seed radiation and compares the profiles with theoretical ones obtained from a radiative transfer model [37U]. The optical system for obtaining temperature and seed atom density in a similar device using emission/absorption measurements of the radiation from the seed atoms is described in Ref. [38U].

CONDUCTION

Contact conduction and contact resistance

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COMBINED HEAT AND MASS TRANSFER

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Acknowledgements—The authors appreciate the invaluable help of Ms Patricia Meyer and Mr Karl Geisler in preparing this Review.