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Heat transfer — a review of 1992 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 1992. It is intended to encompass the English language literature, including English translations of foreign language papers, and also includes many foreign language papers for which English abstracts are available. The literature search was inclusive, however, the great number of publications made selections in some of the review sections necessary.

Several conferences during 1992 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 Center for Heat and Mass Transfer was especially active in organizing meetings and Symposia. The *Spacio-Temporal Structure and Chaos in Heat and Mass Transfer Processes* was discussed in a symposium on 21–24 May in Athens, Greece. A seminar on *Imaging in Transport Processes* was held in the same town on 25–29 May. Proceedings for ICHM symposia are available at Hemisphere Publishing Corp. or at the Center. The *37th ASME International Gas Turbine and Aeroengine Congress and Exposition* (ASME Turbo Expo) contained in its program eight sessions on blade cooling, hot gas path heat transfer, film cooling, and unsteady turbine heat transfer. It was held in Cologne, Germany on 1–4 June. Papers presented at the conference are available at the ASME order department. The *Second International Conference on Advanced Computational Methods in Heat Transfer* was organized by the Wessex Institute of Technology at Milan, Italy on 7–10 July. Papers are published by Computational Mechanics Publications.

The *28th National Heat Transfer Conference and Exhibition* on 9–12 August in San Diego, California discussed in general and poster sessions, panel discussions, symposia, and an open forum topics ranging over the whole field of heat transfer and its applications. The 1992 Donald Q. Kern Lecture was held by Hans K. Fauske on "Prevention and Mitigation of Hazardous Chemical Releases" and the Max Jakob Memorial Award Lecture by Franz Mayinger discussed "Heat Transfer and Bubble Dynamics in Non-Equilibrium Two-Phase Flow". The Max Jakob Medal and the Donald Q. Kern Award were presented to the speakers at a special dinner. Proceedings of the conference are available at the ASME order department or as AIChE title "Heat Transfer", Volume 88, San Diego, 1992. The International Center for Heat and Mass Transfer organized an *International Symposium on Heat Transfer in Turbomachinery* together with a poster session on 24–28 August in Athens, Greece. Conference papers are published by Hemisphere Publishing Corporation. The *First European Thermal-Sciences and 3rd UK National Heat Transfer Conference*, 16–18 September in Birmingham, U.K. presented papers on boiling and condensation, heat exchangers, natural convection, nuclear reactors, combustion, radiation and chemical reactions, convection, fouling, and heat transfer to and from solids. Invited lectures by M. G. Carvalho, M. Cumo, F. Mayinger, and P. le Quéré on numerical methods, high heat flux, compact heat exchangers, and chaos rounded off the program. The *ASME Winter Annual Meeting* took place in 8–13 November at Anaheim, California. Heat transfer sessions dealt with basic processes and with applications like biological heat transfer, gas turbines, powder processing, fire and combustion, heat pipes, environment, non-CFC refrigeration, super-conduction, thermoplastic composites, materials processing and electronic packaging. Heat Transfer Memorial Awards were presented to Vijay K. Dhir, Wataru Nakayama, and Thomas F. Irvine, Jr. Richard J. Goldstein was made an honorary ASME member.

A list of books related to heat transfer and new journals published during 1992 is presented on the following pages. To facilitate the use of the review, a listing of the subject items is made below in the order in which they appear in the text. The letter which appears adjacent to each subject heading is also added to the references cited in each category.

Conduction, A
Boundary layer and external flows, B
Channel flows, C
Flow with separated regions, D
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Experimental methods and devices, E

Natural convection — internal flows, F
Natural convection — external flows, FF
Convection from rotating surfaces, G
Combined heat and mass transfer, H
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Change of phase — condensation, JJ
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Numerical methods, N
Transport properties, P
Heat transfer applications — heat pipes and heat exchangers, Q
Heat transfer applications — general, S
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CONDUCTION

The category on heat transfer involving conduction encompasses a variety of issues whose subcategories include: contact conduction/contact resistance; heat conduction in composite(s) or layered materials and anisotropic media and materials; influence of laser pulse effects and thermal propagations; heat transfer in arbitrary geometries and complex bodies, approaches and models for predicting temperature fields; thermo-mechanical problems; inverse heat conduction; miscellaneous conduction studies; special applications; experiments; and applications to electronic packaging.

Contact conduction/contact resistance

Several important issues involving heat transfer when contact conduction/contact resistance is present appear in literature for a variety of problems. Theoretical, analytical/numerical and experimental papers addressing the physics of contact conduction and contact resistance appear in refs. [1A–17A].

Composite(s) or layered material(s)/anisotropic media

Papers addressing heat contact in composite construction, thermal expansion issues, thermal cracks, multi-layered models, influences due to various heat loads and boundary effects, thermal calculations in composite wall(s) and anisotropic media, effective thermal conductivity approximations, multilayered media, graphite fiber/polymer matrix composites, transverse thermal diffusivity evaluations, thermal resistance in multi-layer composites appear in refs. [18A–39A].

Influence of laser/pulse heat and thermal propagation

The effect(s) due to sudden laser impact on materials, pulse heat loading situations and thermal shock(s) are addressed in this subcategory. Of mention are also publications involving thermal wave propagation problems under the influence of a hyperbolic heat conduction mode. The papers in this subcategory are identified in refs. [40A–53A].

Conduction in arbitrary geometries and complex configurations

In this subcategory, papers dealing with simplified models for homogeneous cylinders, temperature distribution in journal bearings and spherical ridges and troughs in a plane are addressed. These are identified in refs. [54A–56A].

Models/methods and approaches and numerical studies

This subcategory continuos to attract a wide range of interest in the development of accurate models, and modeling/analysis approaches including numerical studies for a variety of physical situations involving heat transfer due to conduction. Finite difference, finite element, boundary element methods and the like have been employed for a wide range of research investigations. These appear in refs. [57A–81A].

Thermo-mechanical problems

The influence of temperature effects on materials and components in particular, thermal-stresses and thermally induced stress waves are addressed in this subcategory. Both linear and nonlinear thermal-stress issues are addressed including theoretical/numerical and experimental studies. These papers are identified in refs. [82A–145A].

Inverse heat conduction

Inverse heat conduction aspects including development of methods, substitution of multi-dimensional problems, prediction under the influence of heat sources and various types of boundary conditions, regularized solutions, explicitly sometimes, numerical approximations and simulations appear in refs. [146A–148A].

Miscellaneous conduction studies

Various types of miscellaneous heat conduction problems have been studied in literature and appear in refs. [149A–178A].

Special applications

Specialized applications involving heat conduction via theoretical, numerical/approximate method sand/or experimental investigations are addressed in refs. [179A–209A].

Electronic packaging

Various theoretical, experimental and numerical studies dealing with thermal heat transfer characteristics, influence of heat sources, contact issues, prediction of temperature field and the like in microelectronic packaging appear in refs. [210A–232A].

BOUNDARY LAYERS AND EXTERNAL FLOWS

The research on boundary layer and external flows during 1992 has been categorized as follows: flows influenced externally, flows with special geometric effects, compressible and high-speed flows, analysis and modeling techniques, unsteady flow effects, films and interfacial effects, flows with special fluid types, and conjugate heat transfer situations.

External effects

Several papers documented the effects of an imposed streamwise pressure gradient [1B, 3B, 10B, 13B–15B]. Some included the effects of acceleration on the stability of the boundary layer indicating conditions of transition and relaminarization. One addressed the effect of agitation. Other effects discussed were variations of the thermal boundary condition, raising of the external (free stream) disturbance level, imposition of longitudinal vortex arrays, and application of sonic disturbances [2B, 4B–9B, 11B, 12B]

Geometric effects

Papers on this topic focused on special effects due to global or surface geometry. Several dealt with rough surfaces constructed of protruding three dimensional elements, heated elements, microscale disturbances, depressions, ribs and stochastic roughness [16B, 19B, 25B, 26B, 29B, 32B, 33B, 34B, 35B]. Remaining papers in this category discussed heat transfer at stagnation points and wedge tips; on curved walls, rotating and stationary spheres, cylinders, and screens; and on moving plates and turbine endwalls [17B, 18B, 20B–24B, 27B, 28B, 30B, 31B, 36B–41B].

Compressibility and high-speed flow effects

One group of papers in this category discussed aerodynamic heating, as experienced by re-entry vehicles, including its effect on the stability of the boundary layer, for various vehicle geometries [42B, 50B, 53B, 58B, 59B, 60B, 63B, 65B]. Several others dealt specifically with the effects of shocks on boundary layer heating [43B–46B, 48B, 51B, 55B, 62B, 66B]. Some discussed turbulence modeling in such flows. Other papers in this category discussed flows on bodies of various shape and through diffusers, flow around bodies in supersonic jets, the stability of the supersonic boundary layers and rarefied gas effects [47B, 49B, 52B, 54B, 56B, 57B, 61B, 64B, 67B].

Analysis and modeling

Analytical papers included the presentation of a form of Nusselt's dimensionless equation, computation of structures in shock tubes, nozzles and open reservoirs and the application of microscale heat transfer [69B, 71B, 78B, 83B, 84B]. Several papers presented turbulence modeling using large eddy simulation, local energy transfer, Brownian particles, renormalization group theory, and tensor diffusivity models [72B, 73B, 75B, 76B, 79B, 81B, 82B]. Remaining papers in this category include analysis of turbine blade flow, including transition to turbulence, and energy equation closure by the turbulent Prandtl number [68B, 70B, 74B, 77B, 80B].

Unsteady effects

One group of papers in this category discussed periodic unsteadiness associated with unsteady thermal penetration, pulsating crossflow, and unsteady heating of the flow [89B, 92B, 97B, 99B, 101B, 103B]. Another focused on the effects of high disturbance level of the oncoming stream, including its effect on transition to turbulence of a boundary layer [85B, 86B, 87B, 93B, 94B, 100B, 104B]. This would also include effects of wakes from upstream objects. Stability of the unsteady flow, flow induced unsteadiness, unsteadily driven object motion, and explosion and implosion effects were also reviewed [88B, 90B, 91B, 95B, 96B, 98B, 102B].

Films and interfaces

Studies of films included papers on stability of falling films and heat and mass transfer to Newtonian and non-Newtonian fluids on plane surfaces and bodies of revolution [105B–111B]. Effects include thermocapillary breakdown and interphase heat and mass transfer.

Fluid types

Results were presented from studies of non-Newtonian fluids in pressure gradients and on continuously moving surfaces and of viscoelastic fluids in steady and pulsatile flow, flows with suction, and flows on stretching sheets [113B, 115B, 116B, 118B, 120B, 121B, 122B, 125B, 127B]. Several papers discussed particle-laden flows in Newtonian and non-Newtonian carrier fluids, including flows influenced by thermophoretic and photophoretic forces [112B, 114B, 119B, 124B]. Other fluid type effects were for supercritical fluids, variable-property flows, dissociated gases, and electrically-conducting gases [117B, 123B, 126B, 128B, 129B, 130B].

Conjugate heat transfer

Several papers on boundary layer heat transfer included conjugate effects. Geometries included a continuous surface, a block, a hot film, and a translating drop [131B–134B].

CHANNEL FLOWS

Heat transfer research in duct flows was subdivided into the following categories: straight-walled circular and rectangular ducts; irregular geometries (annular ducts, ducts with cavities, intersecting channels, semi-circular and triangular cross sections, etc.); entrance effects in duct flows; finned and profiled ducts; flows dominated by swirl and secondary motion; duct flows with oscillating or transient characteristics; multi-phase flow in ducts; non-Newtonian flow in ducts; and several miscellaneous studies including low-temperature applications and high-speed gas flows.

Straight-walled circular and rectangular ducts

A wide variety of physical situations were examined in the relatively simple geometry imposed by straight-walled ducts of circular or rectangular cross section. Numerical studies included Direct Navier–Stokes (DNS) simulations of turbulent transport of a passive scalar, laminar flow modeling using the Extended Random Surface Renewal (ERSR) model, and an analysis of turbulent heat transfer of liquid metal in a tube. Several papers were devoted to new empirical formulations for laminar heat transfer over a range of Prandtl numbers with an emphasis on heat transfer in liquid metals; a new correlation was presented for superimposed forced and free convection in laminar flow. The transitional and relaminarizing flow of combustion gases was examined by several authors. A handful of miscellaneous studies were conducted in straight-walled ducts including: non-MHD laminar flow in a rectangular channel; turbulent liquid flow in a cylindrical channel; the flow of an organic heat carrier under supercritical conditions; and studies of mixing mode heat transfer (radiation–natural convection and forced–free convection) [1C–22C].

Irregular geometries

Complex geometries are ubiquitous and provide unique challenges to the heat transfer research community. Annular flow in straight-walled ducts were considered in a variety of situations including: the effect of smooth and roughened walls on turbulent flow development; the laminarization of turbulent gas flow; heat transfer in an annulus with independent tube rotation; annulus flow with axially translating cores; and the vertical flow in annular channels. Ducts with sudden changes in cross sectional area were examined in an offset channel and in an axisymmetric sudden expansion flow. The complex fluid flow and heat transfer at the perpendicular intersection between ducts in a cooling system was considered. Laminar forced convection was studied in a circular tube having a plate inserted longitudinally; the plate could be rotated about its axis. Other unique configurations investigated were prismatic tubes with nonclassical cross sections, rotating isothermal square channels, and flow in semi-circular and right triangular cross sections [23C–37C].

Entrance effects

Thermally developing duct entrance sections were addressed through a collection of numerical and experimental studies. Mixed axial conduction and convection was analyzed by a finite-difference method; hydrodynamically full developed flow conditions were assumed. A new integral solution was presented for laminar flow heat transfer in the entrance of a circular tube with constant wall heat flux. The combined forced and natural convection was examined numerically in the entrance region of a horizontal square channel. Thermally developing flow was investigated in annular channels, these studies included: the heat transfer to liquid sodium; combined convection and radiation heat transfer; and developing thermal and hydrodynamic laminar flow in an annulus. Entrance effects were also considered in parallel plate configurations and in isosceles and right triangular ducts [38C–50C].

Finned and profiled ducts

Heat transfer augmentation in profiled ducts together with the competing pressure drop penalty virtually guarantees that this area of research will be actively studied for years to come. Applications of finned/profiled ducts were typically in the areas of electronic cooling and gas turbine configurations, however, many studies were very fundamental in nature. Rib-roughened channels in a kaleidoscope of complex geometries were treated in the literature. A brief topical overview of papers included the following: large-eddy simulations in a profiled plane channel; turbulent flow in circular and rectangular ribbed channels; an examination of the periodic placement of rib turbulators; the effect of ribs in a semi-circular duct; pin fin channels with ejection holes; and flow past isolated protuberances and delta-wing elements (vortex generators). A number of studies considered the placement of slanted rib configurations on channel walls; the effects of staggering, full and discrete ribs, and rib height were examined. Finned ducts were investigated for longitudinal configurations and in elliptic ducts. The geometry of star-shaped inserts was addressed for both laminar and turbulent flow conditions [51C–75C].

Duct flows with swirl and secondary motion

Heat transfer augmentation due to secondary motion set up in curved channels was considered in a number of configurations. An experimental study of a curved rectangular duct was made with peripherally uniform wall temperature. A numerical examination of the three-dimensional flow and heat transfer in a square duct turned 90° was undertaken; turbulent flow in a 180° bend was also examined in a combined numerical and experimental effort. The secondary flow in the corner of a square duct was shown to significantly affect the heat transfer in the channel. Secondary motion in helically coiled pipes and the complicated flow in serpentine channels was studied. Several investigations documented the heat transfer characteristics in tubes with spiral or twisted-tape inserts [76C–87C].

Oscillatory and transient flow

Transient and periodically forced flow and heat transfer were addressed in many unusual geometric configurations. Streamwise periodic baffles were used to augment heat transfer; the baffle geometry was carefully studied parametrically. Pulsating flow of aromatic hydrocarbons (e.g. toluene) at supercritical pressures was considered experimentally. Pulsation frequency and amplitude were varied in a study of the heat transfer of liquids in tubes. The effect of self-sustained oscillations in communicating channels was investigated numerically and experimentally. The periodically perturbed flow and heat transfer due to electrohydrodynamical forcing was treated in refrigerant 113. Transient flow was examined in the presence of twisted oval tubes and for time-varying temperature field in a thick-walled pipe [88C–97C].

Multi-phase flow in ducts

Multi-phase flow in ducts was examined in over a wide range of physical situations. Solid–gas two-phase flow was considered in the following studies: submicron particle flow in a cooled laminar tube considering convection, diffusion, and thermophoresis; gas–particle flow of nonisothermal turbulent swirling flow was studied in a cylindrical channel; and mixtures of combustible and non-combustible particles in gas were studied. Gas (typically air) and liquid flow was examined in the presence of wave motion; the interfacial heat transfer was investigated. A new correlation was presented for the air–water flow in horizontal rectangular channels. Air–water flow was also treated in the stratified arrangement found in certain rod bundles. Polydisperse aerosols in cooled laminar flow was studied theoretically and experimentally. Three-phase flow of water (ice–steam–liquid) was examined and compared to single-phase flow. A three-phase system of air–water–sand was also studied in the presence of a tube bundle [98C–109C].

Non-Newtonian flow in ducts

Non-Newtonian fluid flow in ducts was a particularly active research area during the year. Power law fluids in concentric annular ducts were examined, where both the heat transfer and pressure drop were considered. Viscous dissipation effects on heat transfer to power law fluids was studied in arbitrary duct cross sections. Non-Newtonian flow was investigated in a variety of geometries including: axisymmetric sudden expansion (with applications to extrusion processes and capillary rheometry); flow in a rectangular duct (viscoelastic, inelastic, and polymerizable fluids were considered); Couette flow in an annuli with moving outer cylinder (power law fluids); and viscoelastic fluid flow in a screw-wall channel. A second law analysis of non-Newtonian forced convection was also presented [110C–120C].

Miscellaneous duct flow

A handful of studies did not fit well into the categories highlighted above. These investigations included cryogenic applications (e.g. liquid helium), high-speed gas flows, and fluidized bed channel flow [121C–128C].

FLOW WITH SEPARATED REGIONS

Compared to past years there was a very small collection of papers in 1992 devoted to heat transfer in separated flows. While perusing the literature, it became clear that separated flows remain an active research area, but the overwhelming majority of the published work focused on the hydrodynamic features of the flow, and consequently did not fall within the scope of this review. A brief topical outline of heat transfer research in separated flows includes: the three-dimensional flow and convective heat transfer associated with a heated turbulent boundary layer past a streamlined cylinder; the separated flow induced by a strong step-change in surface temperature; heat transfer of flow past a circular cylinder with a trip wire; radiation–convective heat transfer past a backward-facing step; flow past single roughness elements and cavities; and wake flow experienced in turbine blade cascades [1D–14D].

HEAT TRANSFER IN POROUS MEDIA

Porous media means a mixture of fluid and solid phases that have interconnected pores or intergranular spaces through which fluid can move. Such systems are often advantageous because they have a large fluid–solid interfacial area which can enhance physical and chemical processes. As can be seen from the sub-headings in this section, many of the categories are parallel and duplicate the areas covered in other sections of the review. The unifying feature of papers in this section is the essential role of porous media.

Property prediction and measurement

Several theories have been proposed to predict the properties of porous media from those of their constituents [4DP, 6DP, 9DP]. Fractal models are being increasingly used in efforts to discover the relevant scaling laws [10DP, 12DP]. Experiments have been conducted to measure the properties of dry [1DP, 2DP, 7DP, 14DP, 15DP] and moist [8DP, 11DP] porous materials. Transient response has also been used to measure the properties of mixed beds [5DP]. Two studies [3 DP, 13DP] concerned similarity rules or cross-property relations.

Fixed beds (forced convection)

Many applications consider a fixed solid material where fluid is forced through it by an externally imposed pressure difference [17DP, 18DP, 20DP, 22DP, 24DP, 26DP, 30DP, 33DP, 36DP, 39DP]. Many of theses studies involve experiments where the primary objective is to maximize the heat transfer while minimizing the required pressure drop. The statistical nature of the bed properties [19DP, 38DP], phase change [16DP, 23DP], the compressibility of the media [31DP, 32DP] and the temperature dependence of viscosity [34DP] have been considered. Several studied consider fluid flow past a porous surface [27DP, 35DP, 37DP]. Other studies concern numerical techniques for heat transfer in fixed beds [21DP, 25DP, 28DP, 29DP].

Fixed beds (natural and mixed convection)

Many studies considered mixed convection, i.e. combined natural and forced convection [42DP, 47DP, 54DP, 55DP, 56DP, 57DP, 80DP], and some studies considered non-Darcian effects [45DP, 48DP, 63DP, 72DP]. Conjugate heat transfer, i.e. combined convection and conduction, was also considered [60DP, 61DP]. Radiation can also be a significant mode of heat transfer in packed beds [58DP, 81DP, 87DP, 88DP]. Some studies considered two-phase flow in the bed [40DP, 49DP, 59DP, 62DP, 64DP, 65DP, 71DP, 85DP]. Many studies were of natural convection from heated bodies embedded in porous media [43DP, 51DP, 52DP, 53DP, 74DP, 75DP, 83DP], and some considered the effect of tilt of the bodies [77DP, 78DP]. A large number of studies were of natural convection in cavities filled with porous media [41DP, 44DP, 50DP, 66DP, 67DP, 70DP, 82DP, 84DP] where some considered heating from below [46DP, 73DP, 79DP, 86DP]. Some studies were of transient situations [68DP, 69DP, 76DP].

Fluidized beds

Fluidized beds are of great current technological interest, and a large number of articles for the current year are reported. These include liquid–solid, gas–solid and gas–liquid–solid fluidized beds.

Several papers considered the prediction of heat transfer coefficients to liquid–solid fluidized beds [92DP, 107DP, 108DP, 109DP] where the role of voidage formation is emphasized. One studied concentrated on the effective buoyancy and drag forces on particles [106DP]. Another concerned particle granulation [130DP]. The role of the residence time distribution in transient models of liquid–solid fluidized beds was also studied [139DP]. Three papers concerned three-phase (gas–liquid–solid) fluidized beds [111DP, 125DP, 126DP].

The largest number of papers concerned gas–solid fluidized beds. The relationship between particle characteristics, flow velocity, pressure drop and fluidization was object of some study [93DP, 110DP, 127DP, 135DP]. Many papers concerned the measurement and prediction of heat transfer coefficients between the fluidized bed and the wall or immersed bodies in the bubbling regime [100DP, 103DP, 112DP, 119DP, 120DP, 121DP, 122DP, 131DP, 133DP, 141DP] or in circulating fluidized beds [90DP, 91DP, 98DP, 99DP, 117DP, 123DP, 124DP, 129DP, 132DP, 134DP]. Electrodynamic fluidization [94DP] was also investigated. One paper [104DP] concerned the different regimes of heat transfer, and several concerned the transition from bubbling to turbulent fluidization [95DP, 96DP, 137DP]. The two-fluid model was used to calculate heat transfer coefficients [113DP, 114DP] and analyzed using bifurcation theory [105DP]. Models of the quality of fluidization also considered [118DP, 128DP].

Some papers addressed issues in specific applications the largest number being concerned with the fluidized bed combustion of coal [89DP, 97DP, 115DP, 136DP, 138DP]. Others areas of interest include combustion of methane [142DP], catalytic cracking [140DP] and drying [116DP], including vibrating fluidized bed drying [101DP, 102DP, 143DP].

Heat transfer combined with mass transfer or chemical reactions

Numerous studies were done of combined heat and mass transfer in porous media. Several studies considered non-saturated media [156DP, 163DP] where soils [158DP, 165DP, 169DP] and packed bed distillation columns [151DP, 153DP, 160DP] are important applications. Combined heat and mass transfer in saturated media were also studied [144DP, 146DP, 147DP, 154DP, 161DP, 166DP] including salt-finger convection [148DP] and thermohaline instabilities [159DP]. A large number of studies concerned fixed-bed chemical reactors [145DP, 149DP, 150DP, 152DP, 155DP, 157DP, 162DP, 164DP, 167DP, 168DP].

Specific applications

Many paper addressed specific applications of porous media. These papers also could have been included in one of the sub-headings above but are listed here to highlight specific applications areas. The performance of insulation and building materials was extensively studied where moisture transport is often significant [172DP, 181DP, 183DP, 188DP, 191DP, 195DP]. Heat and moisture transfer in fabrics was also studied [184DP, 186DP, 190DP, 194DP, 196DP]. Other applications include coal gasification [176DP, 182DP, 193DP], nuclear reactor thermal blankets [180DP], coal mine fires [192DP], drying of paper [189DP], design of broiler housings [174DP], cryogenic insulation [177DP, 178DP, 179DP], fluidized-bed gasification of rice hull [173DP], storage of milo [170DP, 171DP] and soil heating [175DP, 185DP, 187DP].

EXPERIMENTAL METHODS AND DEVICES

Many experimental results are cited under other categories of this review, and in fact,. papers describing radiation measurements and devices are referenced separately within the radiative transfer section. The objective of this section is to identify papers which focus on new or improved experimental methods or devices for use in heat transfer experiments. Obviously, a wide variety of techniques used to study fluid flow, chemical reactions, and transport phenomena would also be of interest to heat transfer experimentalists; however, to be included here, the papers must discuss some aspect of heat transfer, or provide a general review of techniques which would be applicable to heat transfer measurements.

Heat transfer measurements

Novel methods of measuring heat transfer rates were discussed in a number of papers. Optical methods included quantitative shadowgraphy [3E], fiber optic interferometer probes for measuring surface heat fluxes [7E], photothermal deflection measurements of laser-heated solids [10E], and IR theromgraphy [2E, 4E]. Other measurements of heat transfer coefficients in vessels [8E, 11E], particulate food processing [13E] and IC packages [9E] were presented. Several papers described new heat flux sensors, including bimetallic printed circuits to form multiple thermopiles [6E] and a new technique based on the thermomagnetoelectric effect [5E]. Simultaneous computer modeling was used by several groups to reduce experimental uncertainty [1E, 12E].

Temperature measurements

Only three papers dealt with the ubiquitous thermocouple, so perhaps the community is finally satisfied that it knows how to correctly interpret signals from these sensors. Thermocouple construction [41E], bonding methods [46E], and heat losses and soiling effects in surface thermocouples [39E] were described. Other papers on "well-developed" techniques included analysis of wet bulb temperatures [49E], finned thermometers for faster response [45E], fitting of thermistor equations [24E], and calorimeter methods [25E, 32E, 40E]. Models of temperature sensing methods during metal deformation processes were given in [23E, 26E]. A number of new thin film and probe sensors were detailed [27E, 44E, 47E, 48E], with cryogenic sensors based on resistance thermometry [14E, 15E, 21E, 22E], semiconductor sensors [16E, 29E, 30E], and temperature-dependent capacitance [33E] receiving a great deal of attention. Development of optical techniques for sensing surface temperatures continued, including IR thermography [19E, 20E], liquid crystals [17E, 38E], interferometry [37E], and fast response fiber optic sensors [31E]. Flowfield temperature distributions were measured with holographic interferometry [18E, 28E, 42E, 43E], including a three-dimensional technique involving tomographic reconstruction from a limited number of views [36E]. Other authors presented methods for the simultaneous determination of flowfield temperature and density [34E, 35E].

Velocity, concentration, and flow visualization measurements—single phase

The most commonly encountered experimental techniques used to obtain measurements of velocity include hot wires, laser-Doppler velocimetry (LDV), and particle image velocimetry (PIV), where the latter is capable of measuring two components of velocity, across an entire plane. Much of the development work on these methods has understandably taken place within the fluid dynamics community, and therefore is not within the scope of this review. However, review papers on PIV [51E] and pulsed-wire anemometry [54E], along with new tracer particles applicable for high temperature LDV measurements [64E] may be of interest. Since hot wire measurements and calibrations are essentially heat transfer correlations, we have elected to include those in which the flow temperature was important [52E, 53E, 56E, 59E, 60E, 61E, 62E, 65E, 66E]. Other probe methods to measure velocities were developed to increase ruggedness or decrease complexity compared to hot wires; examples include hydrogen bubbles [50E], dynamic pressures [55E], and cross-correlation of paired thermocouples [63E]. Several reviews on flow visualization techniques may be of interest to the heat transfer community, including one on image processing techniques [58E] and another on structure interpretation of multiple point measurements [57E]. One paper reported on the development of a miniature fiber sensor for liquid mixture concentration measurements in a double diffusive convection system.

Multiphase flow measurements

As with velocity measurements, many groups have reported measurement techniques for use in fluidized or packed beds, bubble columns, and sprays. Some of these papers are cited elsewhere in this review, while many are primarily concerned with chemical reactions or fluid dynamics rather than heat transfer. Several new methods for obtaining turbulent velocity profiles [68E, 69E], and average catalyst particle temperatures in fluidized beds [67E] were reported. A review of Raman and fluorescence techniques for measuring droplet compositions and temperature was given [71E]. In addition, several optical methods for measuring unsteady film thicknesses [70E] and void fractions [72E] in liquid–gas systems were described

Properties

A large number of papers focused on measurements of thermal conductivity and/or diffusivity in solids, and some also measured specific heats. Examples of materials included metals, plastics, glasses, and even diamond films. The majority of these papers described detection methods or analyses of thermal waves generated by pulsed laser heating [79E, 80E, 83E, 90E, 100E, 102E] or other heat sources [78E, 84E, 85E, 87E, 88E, 89E, 92E, 93E, 94E]. Measurement in porous materials were reported in [76E, 99E]. A variety of sensing techniques were employed in liquids, including encapsulated thermistors [77E], photoacoustic [86E], and droplet levitation [73E, 91E]. In addition, a new analytical method was described for organic liquids and mixtures [75E]. One paper described a photoacoustic method for the determination of thermal diffusivities in gases [98E]. Design and operation of calorimeters were described in [74E, 81E, 96E, 97E], including several techniques applicable to cryogenic environments [82E, 95E, 101E].

Miscellaneous methods

Several papers did not fit well into any of the categories chosen above, and yet warrant mention here. These included several non-destructive testing methods to identify thermal characteristics or defects in structural materials [106E] and powder-filled evacuated panel superinsulation [105E]. A procedure to measure the degree of fouling in heat exchanger applications [103E] was also described. Finally, details of cryogenic facilities for testing condensation rates of subcooled liquid nitrogen sprays [104E] and heat transfer processes in a superfluid helium refrigerator [107E] were presented.

NATURAL CONVECTION — INTERNAL FLOWS

Natural convection in enclosed layers of fluid occurs in a number of natural phenomena and in many applications. These include flows in the Earth's mantle, in stellar bodies and in atmospheric phenomena, as well as flows in a number of energy conservation systems of practical interest to engineers. In many instances the flow may be considered isolated from external disturbances offering a very interesting set of physical phenomena in which to study non-linear behavior of the equations of motion with applications to problems in chaos and turbulence.

Horizontal layers heated from below

A horizontal fluid layer heated from below (assuming a normal fluid whose density decreases with the temperature) provides an unstable situation with less dense fluid below more dense fluid. Convection in this geometry is generally called Rayleigh–Bernard flow, named for the two researchers who first studied the problem analytically and experimentally. A range of flows occur from the initial instability when motion starts, to a two- or three-dimensional stable roll and/or cells, to unstable two- and three-dimensional flows, and finally to erratic, perhaps chaotic, perhaps turbulent flow as the Rayleigh number increases. Considerable Rayleigh–Bernard phenomena were reported on in the past year [1F–23F]. These include the stability point at the onset of flow with different types of thermal boundary conditions and the influence of a slight curvature on the bottom surface. Many of the flows studies were experimental using such techniques as Mach Zender interferometry to get three dimensional temperature distributions and particle image velocimetry to study local velocity distributions. A number of secondary instabilities in the flow were studied as well as unsteady three-dimensional convection and the influence of large scale departure from the Boussinesq approximation in an analysis.

Double-diffusive flows

In double-diffusive flows the density difference providing the body force to drive the flow may be due not only to a temperature difference, but also to a difference in the chemical concentration of the species involved. These flows have two diffusion phenomena that must be accounted for in setting up and solving the flow equations. Generally there is diffusion of heat and the diffusion of mass. Recent studies [24F–33F] include flow in square and rectangular enclosures as well as in concentric annuli, the influence of temperature modulation at the boundaries and the study of convection cells that can occur at vertical boundary.

Thermocapillary flows

Thermocapillary flows are often called Marangoni convection. They require the presence of a free or fluid–fluid interface with varying temperature resulting in variations in surface free energy or capillary forces which drive the flow. Often this accompanies a buoyancy-driven flow. Interest in thermocapillary flows [34F–65F] has increased tremendously in the last few years. Many problems have been studied through analysis and/or experiments. Some interest is driven by space applications where thermocapillary forces can be large compared to body forces in low-gravity situation. Others relate to importance of surface tension phenomena in growing crystals. Specific phenomena reported on recently include unsteady thermocapillary flows, and the influence of magnetic field, low Prandlt number fluid and free surface shape on Marangoni convection. Others studies report on various numerical techniques including finite element methods, and the influence of a fluid–fluid interfaces, small aspect ratio, and variable shape boundaries with near zero gravity conditions.

Vertical enclosures — differential heated layers

Buoyancy driven flows in vertical layers of fluid heated by a horizontal temperature gradient contain are described in one of the largest groups of papers in this section of the review [66F–98F]. There are a number of numerical solutions developed to study the laminar flow in various shaped enclosures including cubical and rectangular ones as well as the influence of boundary conditions and having an upper free surface. Transient convection, the influence of the density extremum in water, and modulation of gravity on flows in critical layers have been examined. In addition, optimization of numerical techniques and the influence of vertical as well as horizontal temperature gradients on these flows were considered including instability studies for flow in vertical annuli.

Thermosyphons

Thermosyphons are natural convection loops [99F–101F] that are closed loops of fluid in which the flow is generated due to differences in temperature usually between the two vertical or near vertical legs of the loop. The difference in temperature provides the difference in density that drives the overall motion. Studies include the influence of heating from above and questions on the control of chaos in such loops.

Mixed convection

Mixed convection or combined natural and forced convection are terms generally applied to a flow driven by both buoyancy forces and pressure difference coming from a forced flow. Such flow can provide complex two and three dimensional phenomena. Mixed convection occurs in many real systems even though the original design may have assumed pure forced convection. Recent mixed convection studies [102F–117F] include laminar flow in curved elliptical ducts, and convection in cylindrical annuli, in a vertical duct with asymmetrical wall temperature distributions, in transitional flows near rotating cylinders and in flows with horizontal temperature stratification.

Miscellaneous

A number of other geometries, special conditions, and/or interacting effects with natural convection have been studied which may be lumped together in this potpourri of natural connective flow studies [118F–138F]. These include such things as effects of thermal creep, odd shaped cavities, special algorithms for simulation of three-dimensional convection, cooling of various shaped protrusions and different shaped enclosures, flow in dielectric liquids, flow in super critical helium, influence of radiation on convection in a layer with an odd surface, cryogenic stratification with the influence of various time periodic boundary conditions, general problems of reduced gravity environments, various types of scaling parameters used to study thermal stratification as well as effects of partitions on convective flows.

Applications

Applications of natural convection flows occur in many important systems [139F–152F]. Thus several studies consider the processes in various types of electric cells such as lead acid cells as well as convective electrostatic systems used for copper refining. In addition work has been reported on convective flows in fires important in a number of safety applications, convection in storage tanks that can play a key role related to safety, and vibration effects and convection in solar storage systems when convective flow may be a positive or a negative factor in optimizing long term energy storage.

NATURAL CONVECTION — EXTERNAL FLOWS

Natural convection with vertical plates continues to receive considerable interest. A single system of ordinary differential equations was found using a transformation group for laminar natural convection from vertical surfaces for isothermal, constant heat flux or uniform convective coefficient boundary conditions [67FF]. An analogy between fluid flow and natural convection was developed [47FF]. Parameters that have been studied include the effect of a 45 degree leading edge [33FF], arbitrary heat flux distributions [42FF], flow in a porous medium with constant suction and heat flux on the wall [71FF], and the effects of a fluid with a highly temperature dependent viscosity [24FF]. Heat transfer to a thermally stratified fluid was studied numerically [8FF] and heat transfer through a vertical wall separating two fluid regions was investigated experimentally [34FF] and numerically [69FF]. A numerical method was used to study the transient heat transfer from a flat plate suddenly heated by a radiation heat source [46FF]. An approximate analysis using a Laplace-transform technique was used to investigate heat transfer from a plate oscillating in the vertical direction with a temperature that varies linearly with time [58FF]. Heat transfer enhancements obtained from small protusions [53FF], v-shaped projections [51FF] and a wide variety of projection arrangements [27FF] were found.

Studies of combined heat and mass transfer from vertical flat plates include solutions for boundary layers that form along liquid–gas interfaces [55FF] and helium–air mixtures [18FF] and diffusion in water adjacent to a heated wall [64FF]. A numerical analysis was performed to investigate the plume over a vertical needle with a point source [31FF] and transient heat and mass transfer from a vertical plate of finite height [15FF]. An analytical study on heat and mass transfer to a non-Newtonian fluid was made [30FF] and the onset of convection with combined thermal and electric forces was modeled [62FF].

Turbulence generated by an initial random distribution of density in a fluid was simulated numerically and analytically to describe the birth, life, and lingering death of buoyancy generated turbulence [12FF]. Works that considered turbulent flow adjacent to a heated vertical flat plate include an experimental study of the turbulent structure [73FF], a simulation using a Reynolds Stress model [61FF] and a study of the turbulence production mechanisms in the inner and outer boundary layers [74FF].

The thermal instability of natural convection on upward-facing inclined heated flat plates was studied analytically using linear theory [13FF]. An analytical solution was obtained for natural convection above heated inclined plates in which the surface temperature or heat flux varies as a power function of distance from the leading edge [1FF].

The combined cooling of a vertical channel by natural convection and radiation was studied numerically [54FF]. Experiments were performed on vertical channels with differentially heated sides [25FF] and from an inclined plate with an opposing wall [28FF]. Instability between two vertical plates was investigated using a combination of series expansion and numerical integration techniques [17FF].

A simplified analytical solution was presented for laminar natural convection from a heated, circular horizontal plate [43FF]. An experimental and theoretical study was performed to investigate the influence of a wall around the perimeter of heated horizontal surfaces [44FF].

A heat transfer correlation was developed for natural convection from horizontal cylinders of arbitrary cross section [26FF]. The transient flow about a suddenly heated horizontal circular cylinder was found to consist of an irrotational outer flow and an inner boundary layer flow that formed counter-rotating vortices on opposite sides of the cylinder [70FF]. The flow and heat transfer from a suddenly heated horizontal cylinder confined between two adiabatic vertical plates was simulated using a finite element technique [68FF]. Numerical solutions were also obtained for natural convection from a horizontal cylinder immersed in water near 0°C [76FF] and for a cylinder in an Ellis fluid [22FF]. Experiments were performed to study the effect of circular fins on a horizontal cylinder [35FF] and the influence of a wall on three cylinders in a vertical array [6FF].

An interferometric study was performed for natural convection from horizontal, inclined and vertical cylinders [45FF]. A limiting current technique was used to measure the mass transfer rates from the surfaces of a vertical cylinder of finite aspect ratio [39FF]. Transient effects [75FF] and the influence of wall conduction on turbulent transport [2FF, 3FF] were also studied.

A similarity analysis has been performed to estimate the heat transfer by natural convection with radiative boundary conditions from a wedge and cone [66FF] and from a permeable cone and vertical cylinder [65FF]. A numerical solution was also presented for a porous cone with an isothermal surface [32FF]. An approximate analytical method was used to study the heat transfer from an isothermal sphere [29FF].

Buoyant plume studies include an analytical solution to a two-dimensional line source on an adiabatic wall in a power law fluid [21FF], modeling of vortex rings [7FF] and investigation of a buoyant wake behind a heated body in water [78FF]. The transition of a buoyant plume to turbulence [77FF] was modeled. Several studies considered a buoyant plume in an atmospheric boundary layer [14FF, 49FF, 50FF, 56FF, 57FF]. Flame height and burning front propagation were measured for a variety of surface materials and orientations [9FF, 11FF, 60FF, 72FF].

Mixed convection has been studied numerically for heat transfer from vertical plates in a micropolar fluid [20FF, 23FF], a power law type non-Newtonian fluid [63FF], and measurements have been reported using air [4FF]. A linear theory has been used to predict the thermal instability on horizontal and inclined plates [41FF] and relaminarization of turbulent flow on a vertical surface was proposed [19FF]. A chamber with heat sources and baffles was simulated numerically which modeled an environmental chamber [79FF]. Three numerical studies considered aiding flow around obstructions in a vertical channel representing electronic circuit boards [16FF, 36FF, 37FF]. Numerical solutions were obtained for cross flow over a horizontal cylinder with uniform heat flux [5FF], heat transfer coefficients were estimated for cross flow over electric power cables [38FF] and opposing flow measurements were made near a horizontal cylinder in water [52FF]. An analysis was presented for mixed convection along vertical cylinders and needles [10FF] and for flow near the stagnation point of two-dimensional and axisymmetric bodies [40FF]. Correlations were presented for laminar mixed convection near a line plume and a wall plume [48FF]. Velocity measurements and numerical simulations were made for mixed convection in a horizontal channel with the bottom wall heated and the top wall cooled [59FF].

CONVECTION FROM ROTATING SURFACES

Rotating disks in cavities have been studied numerically with jet impingement [17G] and with protrusions that simulate cobs and a bolt cover [10G]. Experiments using water were made with a jet impinging near the outer rim of a rotating disk [1G]. An analytical approach was used to study a rotating disk in an external forced flow [30G]. The behavior of a thin liquid film on a rotating disk was analyzed [20G, 21G]. Flow through the center of rotating disks simulating the area near a shaft was investigated in a test rig using air [3G]. Turbulent flow and heat transfer near a rotating surface was predicted using various turbulence models [15G, 26G].

Numerical studies were performed to investigate the thermal and hydrodynamic entrance region in rectangular channels rotating about an axis perpendicular to their centerline [2G, 9G]. Solutions were also obtained for the fully developed turbulent flow region [18G]. Experiments were made with different channel wall temperatures [6G], trips in the flow passages [27G] and under superconducting conditions using helium [16G]. Experiments were made with a circular tube rotating about an axis orthogonal to its centerline to study the Coriolis and buoyancy effects [14G].

Theoretical studies on thermal convection in a rotating fluid layer include an asymptotic theory for the limit of rapid rotation [29G], stability with helical turbulence [24G] and instability with a micropolar fluid [19G].

Studies of rotating annuli include a numerical study of mixed convection in vertical annuli with the inner cylinder rotating [8G], measurements of periodic and chaotic flow regimes in a horizontal rotating annulus [22G], and the effect of axial grooves on either of the cylinders [7G]. A matched asymptotic expansion method was used to study the heat transfer enhancement through counter-rotating eccentric cylinders [4G]. Concentric and eccentric annuli were studied for moderate and low Prandtl number fluids [11G, 12G, 13G].

Studies of cylinders rotating about their axis include a theoretical study of mixed convection in a vertical rotating cylinder [5G] and the effect of rotation on turbulent flow inside a rotating, insulated pipe subject to external forced convection [28G].

Measurements of mixed convection about a rotating sphere were made using holographic interferometry

[25G] with the axis of rotation ranging between vertical and horizontal. Heat transfer from an array of rotating cylinders was investigated theoretically [23G].

COMBINED HEAT AND MASS TRANSFER

These areas of investigation include a number of problems in convective heat transfer. Generally there is a transport process involving diffusion and convection of both heat and mass and/or there is a flow of mass through a surface as in transpiration, film cooling or ablation, or flow of mass to a surface as in jet-impingement heat transfer.

Transpiration

When a flow occurs through a wall we say the fluid transpires through the surface; this is particular true if the flow is nearly continuous across the surface as could occur with a porous wall, for example. In transpiration cooling a relatively cold fluid enters the mainstream through a porous wall. This flow could be used to cool a wall over which hot combustion gases flow. The injected fluid (often air) mixes in the boundary layer lowering the temperature in the inner portion of the boundary layer and thus at the wall surface itself. Transpiration has been studied over a wide range of conditions [1H–12H] including flow into a hypersonic air stream. One study considered the use of transpiring fluid to support the freezing of a liquid. Many of these studies have been analytical and numerical, often seeking optimization of the flow parameters to minimize the amount of transpired fluid that need be used to cool a wall. Experimental studies generally seek to obtain the heat transfer conditions over a significant range of flow conditions. In some related studies reverse flow occurs; there is a suction of gas through the surface drawing fluid from the boundary layer into the wall.

Film cooling

In film cooling [13H–30H], flow passes through a solid surface as in transpiration cooling. The aim is to protect the surface from a hot gas stream flowing over it. However, the "coolant" rather than being injected continuously across the surface enters at discrete locations. These may be one or more slots across the whole span of the flow. More often it is one or more rows of holes. In the special case of full surface film cooling, there is an array of small holes in the surface through which flow enters. In the limit of a very dense array this could approach "transpiration flow". Whatever the geometry the injection or coolant flow mixes with the boundary layer lowering its temperature. Studies on film cooling in the last decade have been mostly directed towards problems in high temperature gas turbines. It has become a favored method of protecting the first stage components of the turbine from exposure to high temperature combustion gases. Film cooling has been studied for cooling of turbine disks as well as cooling of blades themselves. It is also being utilized on flame tubes and combustors. Some studies consider the influence of swirling flow, density difference, and what occurs on the turbine endwall in a film cooled system. Influence of the geometry of the section has also been examined.

Impingement heat transfer

Impinging jets are used in a number of cooling systems [31H–67H] generally because of the thin boundary layer near the center of the impingement which provides high local the heat transfer coefficient. One can pin point the location of peak heat transfer, directing the jet or jets to the region where heating is a maximum and major cooling is required. A number of studies consider the impinging of submerged jets in which the jet is essentially the same as the ambient fluid. Studies on impingement cooling of submerged jets include consideration of the influence of cross flow on laminar slot jets, and the turbulence characteristics of jets; a variety of works are related to numerical modeling of jets. The influence of swirling flow, cooling of wedges and rib roughened walls as well as two phase gas particle jets have been studied with various surface configurations. Other phenomena of interest included the influence of boundary layer turbulence and the application of various turbulence models to predict impingement heat transfer.

Liquid jets [68H–75H] because of their relatively high density and specific heat, can be very effective coolants. Studies of the heat transfer from impinging liquid jets include the influence of capillary instability, spattering jet geometry, and condensation on the local and average heat transfer from the surface.

Spray cooling

In spray cooling, liquid droplets impinge on a surface. Heat transfer occurs both to the liquid drops and the carrying gas as well. Spray cooling studies [76H–81H] include the effect of evaporation of liquid droplets and studies of the flow of the liquid after impingement, as would occur in a mist flow.

Drying

In drying systems there is close interaction between the heat transfer and mass transfer. Drying has been studied [82H–113H] for a number of applications including cooling of ceramic beads, papers, cereal grains and many different foods. Much of this work is empirical. Others studies including those on the drying of paper sheets and woods have major applications in industry for which fundamental knowledge is being compiled and examined.

Miscellaneous

Other papers [114H–122H] have reported on studies of a variety of problems which involve simultaneous heat and mass transfer. These include studies on falling films, evaporation from solid surfaces, and some special heat and mass transfer devices.

CHANGE OF PHASE — BOILING

Thermal transport phenomena, associated with liquid-to-vapor phase change, continue to attract significant attention in the heat transfer community, though at somewhat reduced levels than in previous years. The 1992 archival english language literature reflects considerable activity in evaporation from droplets and films (31 papers), pool boiling (61 papers), and flow boiling (45 papers). More modest publication rates were encountered in the subcategory of bubble characteristics and boiling incipience (14 papers), as well as in two-phase thermohydraulic phenomena (9 papers). In addition to the 161 papers dealing with evaporative and ebullient heat transfer, surveyed in this section, the interested reader will find reference to these phenomena in some of the 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 evporation

The evaporation of small, single drops is of special importance in internal combustion engines and turbomachinery, as well as in various chemical process, drying, and air-conditioning equipment. During this review period, archival studies of the evaporation rate of a single isolated droplet included: determination of the transient temperature field on a semi-infinite solid [5J, 10J], the effects of liquid viscosity [30J] and gas pressure [9J], the impact of a chemically active atmosphere [16J], and several studies on the evaporation of a two-phase drop in an immiscible liquid [14J, 15J, 23J, 27J]. Taylor instability effects on the explosive evaporation of a liquid metal drop were addressed in [8J]. Drop-to-drop interactions and drop-to-wall interactions were studied in refs. [3J, 20J, 29J] and [11J, 26J], respectively, while refs. [4J, 13J] examine the behavior of evaporating droplets in a convective boundary layer.

The successful design of refrigeration, distillation, desalination, and food processing equipment often requires an understanding of thin liquid film evaporation. A comprehensive review of available correlations for tubes and tube banks was presented in ref. [28J]. The behavior of an evaporating meniscus was examined in refs. [22J, 24J, 25J], the stability of evaporating films in the presence of surfactants in ref. [6J], the evaporation of a binary film in ref. [2J], and evaporative heat and mass transfer in falling liquid films in refs. [1J, 7J, 12J, 18J]. The influence of surface characteristics on evaporative spray cooling was the subject of ref. [19J], the effect of steam concentration on the evaporative drying of wood residue is examined in ref. [21J], and the effect of evaporation on laminar heat and mass transfer in a channel in publication [31J]. A methodology for the quantitative evaluation of the explosive vaporization potential of contained liquids is presented in ref. [17J].

Bubble characteristics and boiling incipience

An understanding of bubble formation, growth, and break-up is essential to the design and optimization of equipment and processes in the chemical and metallurgical industries. In ref. [45J] heterogeneous nucleation was found to resemble detonation phenomena. Bubble formation by cavitation and at the interface between two immiscible liquids was the subject of refs. [42J, 43J] and [39J], respectively. The influence of microgravity on bubble departure diameter was documented in ref. [38J]. The contribution of microfilm evaporation to bubble growth is studied in ref. [44J], while diffusion-induced bubble growth in viscous liquids is the subject of ref. [32J]. The dynamic characteristics of bubbles were examined in several studies, including: free bubble oscillations in high-polymer solutions [40J], ultrasonic forced oscillations in polymer solutions [41J], acoustic oscillations in an ideal incompressibe fluid [35J], freely rising spheres [36J], and the rise characteristics of bubbles in a liquid undergoing flash evaporation [34J]. Other studies in this category addressed the modeling of mass and heat transfer between vapor bubbles and liquid during rectification [37J], and methods for finding average transfer coefficients for non-linear transport between bubbles and the surrounding liquid [33J].

Pool boiling

Interest continues in thermal transport by pool boiling from immersed surfaces, with growing emphasis on cryogenic applications, use of refrigerants, and studies of enhancement techniques. Wall temperature patterns and nucleation site density in nucleate boiling were examined in refs. [63J] and [48J], respectively, the nucleate boiling mechanism in ref. [100J], and the effects of microgravity in ref. [79J]. The influence of transient and pulsed heating was studied in several investigations, including transient boiling behavior of R113 under microgravity conditions [53J], the pulsed boiling of helium [54J, 88J], and transient boiling of nitrogen with various heat inputs [87J]. References [66J, 67J] discuss the effect of wetting and heater material on the pool boiling of hydrogen and nitrogen, respectively, and ref. [64J] the pool boiling of helium, while ref. [86J] deals with the extrapolation of water data to helium, accounting for variations in contact angle, ref. [72J] relates to boiling on the boundary between two immiscible liquids and ref. [93J] to nucleate boiling of R113 on a porous surface. The boiling of liquid mixtures is the subject of refs. [59J, 92J]. Pool boiling on downward facing and inclined surfaces was explored in ref. [56J], in a small tube bundle in ref. [73J], in rotating tubes [106J], from a partially-immersed surface in ref. [104J], in perforated vertical plates in ref. [99J], and boiling-like behavior in heat transfer to bubble-layers in ref. [46J].

Studies of pool boiling enhancement continue to occupy a large number of investigators. The literature surveyed provides insight and data for the effects on pool boiling of surfactants in polyacrylamide solutions

[101J], silicon re-entrant cavities for R113 [82J], a particle layer coating for FC-72 [105J], horizontal confinement of the boiling liquid [70J], the use of ultrasonic waves [57J] and imposed vibration [90J, 83J]. The benefits of covering a surface with metal spheres [74J] and metal cylinders [52J], the use of thermally-enhanced tubes [103J], and the results of combining vertical confinement and a sintered porous layer on the surface [102J] are also described.

Nucleate pool boiling terminates at the so-called critical heat flux (CHF], when vapor bubbles/columns blanket the surface and lead to severe deterioration in the heat transfer coefficient. Several fundamental studies of CHF, addressing the effect of liquid/solid contact [96J], surface geometry [85J], initial macrolayer thickness [84J], and macrolayer growth [77J], as well as the development of a CHF calculational procedure [51J], are reported in the literature. CHF at the bottom of a closed vertical tube [62J], in a two-phase thermosiphon [94J], and from millimeter-sized heaters [68J] has also been studied. Enhancement of pool boiling CHF, via induced convection along a partially heated plate, in the presence of a low conductivity coating, and with the use of a porous coating, is described in refs. [49J, 61J, 71J], respectively. A CHF-like phenomena, boiling-up of an enclosed gassy liquid, is examined experimentally and analytically in refs. [89J, 91J, 76J, 95J].

At surface temperatures substantially greater than those associated with CHF, film boiling prevails along the heated surface. Liquid–solid contact during film boiling was measured in ref. [58J] and the effects of transient heat generation in refs. [75J, 81J]. Much of the film boiling literature deals with geometric effects, including subcooled film boiling on a vertical surface [97J, 98J], along a horizontal surface [55J], from horizontal cylinders [50J, 78J, 69J], and from a rotating sphere [80J]. Thermal explosions associated with film boiling liquid metal–water systems are explored in [47J] and film boiling in spray cooling in refs. [60J, 65J].

Flow boiling

Heat transfer in flow boiling is intimately related to the mass fraction of the vapor and the prevailing flow regime. Boiling phenomena are, thus, strongly influenced by the enthalpy of the coolant, the orientation of the channel, and the geometry of the heated surface. While efforts continue in the development of flow boiling correlations [143J] and analytical calculations [151J], much of the literature deals with flow boiling of binary mixtures [132J, 141J], and flow boiling in specific geometries — such as tube bundles in vacuum [142J], rotating axial channels [150J], and arrays of protruding heat sources [120J], as well as techniques for flow boiling enhancement — such as spirally fluted tubes [134J], enhanced annuli [139J], and high-porosity channel inserts [118J]. The onset of nucleate boiling in reactors [112J], the effect of nucleate boiling on sediment formation [121J], and studies of flow boiling heat transfer in microgravity [137J], under impinging water jets [144J], and in copper laser targets [124J] are also reported.

The 1992 archival literature reflects the substantial interest in the prediction and enhancement of flow boiling critical heat flux. A relatively large number of papers review the available mechanistic and phenomenological models for CHF in channels [111J, 119J, 126J, 127J, 145J, 148J, 149J] and on external cylindrical surfaces [138J]. An extension of the Katto model to low pressures is offered in ref. [123J], while ref. [113J] describes the development and validation of a microscale CHF computer code. Recent experimental studies have examined CHF in horizontal tube bundles [114J, 129J], in vertical tubes under transient conditions [110J], in nuclear reactor fuel bundles [130J, 131J], in coil steam generators [122J], in asymmetrically heated channels [109J], and in channels with discrete heat sources, simulating electronic components [117J, 146J, 147J]. References [116J, 125J] explore the potential for enhancement of CHF by centrifugal forces and turbulence generators, respectively.

Experimental studies of post-CHF flow boiling addressed film boiling behavior in horizontal flat ducts [136J] and tubes [135J], transition boiling on spherical heaters [133J], and film boiling in the stagnation region of a molten drop [115J]. Attempts to model flow film boiling are reported in refs. [107J, 108J, 140J] and an investigation of porous layer enhancement of post-CHF behavior in ref. [128J].

Two-phase thermohydraulic phenomena

The study of the thermal phenomena associated with flow-boiling can not be divorced from the analysis and/or prediction of the relevant thermohydraulic parameters. Publication [157J] reviews the status of the two-fluid models, ref. [159J] an analysis of of flooding in parallel channels, ref. [158J] the development of a two-phase shear layer integral calculation method, and ref. [160J] a theoretical study of interfacial area in bubbly flow. While methods for void fraction prediction in subcooled flow boiling channels were discussed and compared in ref. [153J], void fraction variations in adiabatic flows are examined in refs. [152J, 156J]. Additional studies address the prediction of pressure fluctuations [155J] and pressure drops [154J].

CHANGE OF PHASE — CONDENSATION

Papers on condensation in 1992 dealt with surface geometry, system global geometry, and boundary conditions effects. Techniques for modeling and analysis were presented in addition to experimental results for film and free-surface condensation. Several studies investigated unsteady effects and, again this year, binary mixture condensation was a popular topic.

Surface geometry effects

Several papers reviewed the effects of finned, grooved, ribbed, and corrugated surfaces, often contrasting the performance with that on plain surfaces [1JJ–7JJ]. Others discussed condensation on particle surfaces, porous surfaces, and fog nuclei [8JJ–12JJ].

Global geometry and thermal boundary condition effects

Effects of geometry, including vertical pipes, and bundles and horizontal tubes and tube banks, inside and out, were investigated [13JJ–24JJ]. Other geometries included vertical plates, axisymmetric bodies, and the inside of a thermosiphon [25JJ–29JJ].

Analysis

Papers on this topic discussed analysis or modeling of reflux condensation, film condensation, droplet coalescence and growth, droplet-on-surface behavior, and viscosity variability effects [30JJ–37JJ]. One discussed several factors which were overlooked in deriving correlations. Another applied kinetic theory to develop relations for jump coefficients in the vapor phase between an evaporating and a condensing surface.

Free surface condensation

Papers in this category discussed condensation on the liquid–vapor interface of condensing bubbles, growing droplets, and sprays in isothermal flows and flows passing through thermal gradients. Other geometries included falling liquid films, jets, and a free interface in a water/wind tunnel [38JJ–44JJ].

Transient effects, including nucleation

Transient effects which were discussed in the 1992 literature include: oscillating noise, response to a rapid pressure decay, and deposition of potassium in MHD channels [45JJ–49JJ].

Binary mixtures and property effects

Studies on mixtures in laminar films (including water–LiBr mixtures), mixtures in capillary spiral passages, and two-component gas mixtures (including one with water and carbon dioxide) were presented [50JJ–54JJ].

CHANGE OF PHASE — FREEZING AND MELTING

In this section, numerous theoretical, analytical/numerical and experimental studies in which phase change processes — freezing and melting — are reviewed. The sub-sections are categorized as Stefan problems; solidification and binary mixtures: alloys and continuos casting processes; solidification in crystals and directional solidification; freezing and melting; frost, ice, water, snow, soils, salts, films; freezing/melting; welding and thawing: applications; convection effects; continuos casting processes and mold filling; methods, models and numerical studies; special experimental/analytic and/or comparative studies; thermal storage; and miscellaneous applications.

Stefan problems

Stefan problems involving pressure–temperature effects, boundary conditions influences, approximation methods and iterative solution formulation appear in refs. [1JM–5JM].

Solidification and binary mixtures: alloys/metals and casting processes

Numerous papers appeared this year encompassing various aspects in which phase change issues in metals and alloys and casting processes. These papers encompass a wide variety of issues including theoretical, numerical, and experimental including specialized approaches to observe and capture phase change situations. The numerous applications include metal, alloys, binary mixtures and compounds and the like. Papers appearing in this subcateogry are identified in refs. [6JM–33JM].

Solidification in crystals and directional solidification

Like in past years, there has been a significant amount of research activity and investigation addressing a variety of issues involving crystals and issues regarding directional solidification since it is beyond the scope of this review to isolate each contribution, the reader is encouraged to refer to papers in this subcategory which include research activity encompassing stability, boundary layer influence, temperature computations, shrinkage pressure effects, convection, heat and flow effects, dendrific growth and the like [34JM–74JM].

Freezing and melting: frost, ice, snow, water, soils, salts, films

Freezing and melting under various situations involving phase change in frost, ice, snow, water and the like are outlined in this subcategory. The research activity included density effects in water, natural convection on ice formation, heat transport in soils, freezing in soils, models, numerical simulations, de-icing issues and the like. These appear in refs. [75JM–102JM].

Freezing, melting/thawing, and welding: applications

Papers appearing in this subcategory encompass optimization during decay of metal melts, electro-beam welding, cellular interfacial patterns involving phase change, freezing and thawing in cooked cylinders, melt solidification on material surfaces, stirring of melts and laser induced effects. These appear in refs. [103JM–111JM].

Convection effects

In addition to phase change processes involving the mode of diffusion only, the effects due to convection play an important role in many applications [112JM–120JM].

Casting processes and continuous casting

This subcategory addressed relatively few papers and are included earlier in the subcateogry on solidification: alloys, metals and casting processes.

Models/methods and numerical studies

Analytical models and numerical simulations involving phase change continue to be an important aspect in the prediction of temperature fields, phase front locations, and the like. Papers in subcategory include enthalpy formulations, variation approaches, finite elements, and boundary elements approaches, analytical formations, one- and two-phase melting problems, simulations in crystals, metals and liquids [121JM–150JM]

Special experimental/analytic and/or comparative studies

A comparison of calculation methods and study of heat and mass transfer during hydrogen sorption–desorption in metal–hydride elements of power plants appears in ref. [151JM].

Storage Devices

Heat transfer enhancements in a thermal storage device appears in [152JM–153JM].

Miscellaneous studies involving freezing/melting

A wide variety of investigations involving freezing/melting and special applications appear in [154JM–198JM]

RADIATIVE HEAT TRANSFER

Papers reviewed in this category are related by their primary concern with radiative heat transfer. Modeling efforts have continued to play large roles within the areas of combustion systems, atmospheric radiation, materials processing, coatings and insulating materials. As would be expected, the number of full scale experiments in the former two areas are limited, but a number of investigations have been conducted to verify specific aspects of the models. The subcategories below are broken down into both general techniques and specific applications, depending on the emphasis of the paper. Therefore, related papers may be found under several subheadings, and cross references are given where appropriate.

Enclosures and multi-dimensional models

A variety of numerical techniques were developed to model radiative transfer in enclosures. Discrete-ordinates [7K, 8K, 10K, 15K, 16K] and spherical harmonics approximation techniques [11K, 12K] continue to be popular in both rectangular and cylindrical geometries, while a fairly wide range of techniques are being persued to handle arbitrary geometries [3K, 4K, 6K, 17K, 19K, 21K]. An analytical solution was presented for the case of a sphere in a concentric cavity [2K], and non-spontaneous radiative transfer was described within certain geometries [13K]. General techniques applicable to curvilinear coordinate systems [9K, 20K] were described, and the Galerkin method was applied to inhomogeneous layers [1K]. Application specific results were given for wall-to-random-bed view factors [18K], attic barrier systems [5K], and optimization of radiator surfaces [14K]. See also the section on combustion systems.

Radiative transfer in participating media

The papers in this subsection emphasize techniques used to model radiative transfer in absorbing, emitting, and scattering media. (Note: several of the papers in the preceding section and many of those involving combustion also include participating media.) Many of this year's papers address spatially varying properties and/or multiple scattering. Improved methods for Monte-Carlo [39K], moment (i.e. F_n) [28K, 42K], and spherical harmonics (P_n) [37K, 44K] formulations were presented, along with an adaptation of the Schrödinger equation to radiative transport [29K]. Applications to curvilinear geometries included laser beam propagation [24K, 40K], rocket plumes [38K, 43K], and rapidly expanding spherical shells (e.g. supernovae) [30K] were presented. Applications to planar geometries were dominated by atmospheric transport with multiple scattering [31K, 46K, 47K, 48K, 49K] and spectral models [26K], but refractive index effects in planar materials [41K] and inverse analyses [35K] were also considered. Other papers documented models of radiative transport in random media with applications to fibers, particle-laden systems, and packed beds [22K, 23K, 25K, 32K, 33K, 34K, 45K], turbid media [36K], and remote sensing of plant canopies [27K].

Radiative transfer in hot gases and plasmas

Several papers modeled radiation from gas jets and flows [50K, 51K, 58K], while analytic formulas for radiation trapping in planar media were given in ref. [57K]. Non-equilibrium considerations dominated investigations of re-entry [52K, 53K, 54K] and plasmas [55K, 56K]. (See also the participating media and combustion papers.)

Flames, fires, and combustion systems

The papers in this subsection could be considered as subsets of the participating media and hot gas headings, and many of the combustion systems involve enclosures. However, since combustion processes are common to all of the papers here, they have been grouped separately. A number of numerical methods for coupling radiative heat transfer to flame models were presented [64K, 71K, 72K, 74K, 79K, 84K]. Several other papers examined radiative transfer during ignition [77K] and explosion [63K] processes. Experimental measurements and analyses of sooting pool fires were presented in refs. [75K, 78K, 81K], while ignition characteristics due to nuclear explosions and neighboring fires were modeled in refs. [65K, 73K]. Models of coal combustion [60K, 69K, 76K, 82K], fluidized beds [61K, 66K], and solid fuel rockets [85K] were also given. A number of papers proposed methods for augmenting, reducing, or redistributing the heat transfer to tubes [59K, 68K, 70K, 80K] and walls [67K, 83K, 86K] of furnaces and boilers. Finally, one paper detailed a narrow spectrum model for application in furnaces [62K].

Radiation with conduction or convection

This section includes instances in which radiation is combined with or coupled to conductive or convective modes. Eleven papers considered conduction, including five studies of various types of planar layers [88K, 89K, 92K, 94K, 103K], and two on solid cylinders [101K] and concentric spheres [90K]. Microwave heating [87K, 95K], transient cooling of semitransparent square media [100K], and radiation-induced explosion of water droplets [99K] were also examined. Seven papers explored convection, of which two involved planar geometries involving absorbing/emitting layers [102K] and heat shields [91K]. Aerosol applications included correlations for combined heat transfer from a sphere [97K], modeling of thermophoretic motion in laminar boundary layers [96K] and gas–particle interactions in shock-heated aerosols, and numerical analyses of participating media in rectangular enclosures [93K, 98K].

Radiative transfer to/from surfaces

A number of papers focused on interactions between laser beams [106K, 107K, 112K, 114K] or incoherent radiation [104K, 115K, 116K] with substrates and films. Several other papers presented models of radiative exchange between surfaces of various geometries [105K, 109K, 110K]. Both forward [113K] and inverse [108K] problems involving radiation from gray and blackbody surfaces were solved, and a technique for estimating maximum temperatures in polymers was given [111K].

Radiative properties

Properties of interest in radiative in radiative transfer problems include reflectivity, absorptivity, transmissivity, and emissivity, as well as scattering cross-sections. The following papers report directional or spectral values of these quantities for various materials. (See also the Experimental Methods subsection for descriptions of techniques used to measure properties.) Models predicting the properties of multilayer films [137K, 138K] and coatings [121K, 124K, 139K, 142K] were presented, along with a ray tracing method to predict spatial variations in directional emissivity of axisymmetric bodies [129K]. Measurements of temperature-dependent properties of semiconducting and superconducting films [122K, 125K] were reported, as were the scattering properties of thermochromic gels [118K]. Bulk material properties were given for sea water [140K], ice [135K], glass [119K], fibers [126K], metal fluoride crystals [141K], metals and alloys [117K, 127K, 131K, 134K, 136K]. Properties in combustion systems associated with soot [120K, 128K, 133K], fly ash [130K, 132K], and CO_2 [123K] were also reported.

Experimental methods and devices

A large number of papers dealt with radiometers, ranging from optimization of measurement methods [148K, 162K, 163K, 165K] to calibration sources and procedures [143K, 145K, 146K, 149K, 157K]. Novel techniques applicable to thermography [159K, 166K, 167K] and pyrometry [144K, 147K, 150K, 153K, 154K, 156K] were also presented. Several new sensors, including some superconducting ones, were described in refs. [151K, 152K, 158K, 171K], along with a technique to measure the responsivity of IR detectors. Measurement techniques for obtaining the optical properties of thin films [164K, 168K], solids [155K, 169K], and fibers [170K] were also reported. Details of temperature measurements in flames using a modified real-time line reversal technique [160K] and atomic emission/absorption measurements in an MHD channel were documented. Finally, the design of a moderate temperature IR absorption cell was discussed [161K].

NUMERICAL METHODS

One of the rapidly growing areas of research is numerical methods. The development of a wide variety of methods and their application to physical problems form major research activities in many aspects of heat transfer. 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.

Heat conduction (direct problems)

Heat conduction provides a fundamental testing ground for the development and evaluation of numerical methods. Therefore, new methods are often presented in the context of heat conduction.

A number of papers [1N–9N] deal with direct heat conduction problems. Attention is especially given to the accuracy of calculating time-dependent heat conduction. Both the finite-difference and finite-element methods have been employed.

Heat conduction (inverse problems)

Some papers have given attention to inverse heat conduction problems, in which the problem specification is extracted from some knowledge of the solution. The papers [10N–12N] deal with inverse heat conduction, with one paper using the boundary element method.

Phase change

Development of numerical methods for solid–liquid phase change is described in [13N–22N]. The enthalpy method is commonly used for the determination of the interface. In these problems, natural convection usually plays a dominant role. Some methods employ boundary-fitted coordinates to handle irregular geometries.

Convection and diffusion

The differential equations for all the relevant variables for fluid flow and heat transfer contain convection and diffusion terms. The accuracy and reliability of a numerical method depend largely on the proper formulation of these terms. Therefore, improved formulations of the convection–diffusion terms are still being worked out. The papers dealing with this topic either present new schemes or evaluate a number of chosen schemes [23N–48N]. The topics range from the standard central and upwind schemes to different high-order schemes including a number of variants of QUICK. The objective of most of the new techniques is to reduce or eliminate false diffusion without losing the boundedness of the solution.

Multigrid techniques

The solution of complex physical problems requires a large number of grid points. This invariably slows down the common iterative methods for solving the equations. A possible remedy is the use of multigrid techniques, which retain their efficiency even when a very large number of grid points are employed. The papers dealing with multigrid techniques [49N–56N] apply the procedure to convection–diffusion problems, curvilinear coordinates, and complex geometries. Often it is shown that the multigrid methods provide convergence rates that are far superior to those given by a single grid method.

Radiation

Since thermal radiation is governed by equations that are far more complex than the equations for other variables, special numerical techniques are required for handling the radiation equations. Radiation in a participating medium is considered and numerical methods are presented [57N–60N] for the solution of the radiation intensity.

Solution of flow equations

The connection between convection and fluid flow is obvious. Therefore, any method for the calculation of convective heat transfer needs to make a provision for the solution of the flow equations. Since the literature on numerical methods for fluid flow is extensive, only the papers relevant to heat transfer are considered here. These papers [61N–78N] deal with finite-volume methods on staggered and nonstaggered grids, finite-element methods, unstructured grids, boundary fitted coordinates, and domain decomposition. A number of variants of the SIMPLE algorithm have been proposed and tested. Benchmark solutions have been presented for some standard problems. Some methods deal with the determination of free surfaces.

Turbulent flow

Practical computations of many flows require the use of a turbulence model, which brings additional numerical considerations. The issues involved in the computation of turbulent flows are discussed in refs. [79N–86N]. Whereas the k–e model is the most common choice, algebraic stress models and large eddy simulation are also used. Models have been proposed for turbulent heat transfer, stably stratified flows, and strongly swirling flows.

Other studies

Various other topics have been addressed in refs. [87N–92N]. These include the flow in constricted tubes, saturated porous layers, and oscillating flow and heat transfer. A method for thermal/structural analysis is presented. A study pertains to the choked and nonchoked compressible flow between closely spaced plates. Solutions for the shear driven cavity have been presented for high Reynolds numbers.

TRANSPORT PROPERTIES

Research in transport properties continues to be concentrated on thermal conductivity for pure substances and mixtures through experiments and analytical correlations.

Thermal conductivity

A number of papers report measured values of the thermal conductivity coefficient; vapors of iso-alcohols, allyl-alcohol and cyclopentanon; liquid ether; the thermometric materials — chromel, alumel, and constantan — and chemical-vapor-deposited diamond films [13P, 14P, 21P, 29P, 32P]. Thermal diffusity and thermal conductivity values are reported for high temperature liquid metals, molten alkali halides, and single crystal lanthanum aluminate [15P, 19P]. In several of these efforts a laser flash or transient heat-pulse technique has been used.

Steels, austenitic and low carbon, titanium and titanium alloys have been studied [24P, 33P], in some instances at cryogenic temperatures. For composite systems results are reported for woven metal lattices, natural zeolites, and binary systems of mixed, compacted powders of NaCl in low-density polyethylene [3P, 17P, 25P]. Other works treat copper–tin and nickel–tin intermetallics, a cordierite-based ceramic, aqueous salt solutions at high temperatures and high concentrations and concentrated, sterically stabilized, colloidal suspensions of alumina powder in paraffin oil [9P, 10P, 27P, 31P]. Also studied were polyolefins and halogenated-substituted polymers and silicone rubber [4P, 26P].

A number of papers report the results of transport property calculations using a molecular dynamics approach. Noteworthy are a review of nonequiblibrium and equilibrium molecular dynamics approaches to both Newtonian and non-Newtonian fluids, new expressions for thermal conductivity of a multicomponent mixture of polyatomic gases and the influence of moderate pressure on pure, polyatomic gas thermal conductivity [8P, 12P, 16P, 23P, 28P, 30P]. Useful computerized correlation (MIPROPS) of thermodynamic and transport properties, based on a modified Benedict–Webb–Rubin equation, originally covering 11 fluids, has been extended to 17 common substances [6P] and another summary of experimental data considers nitrogen, oxygen and air [1P]. Another review paper considers the status of laser-spectrometric methods for obtaining transfer coefficients [18P]. Specific thermal conductivities are calculated for: pyrophyllite, drying porous media, modified polyvinylchloride, amorphous substances, alkaline rare earth dimolyedates, thermoelectric materials in semiconductor thermobatteries, magneto-optical recording film and thermoelectric $Si_{0.8}$–$Ge_{0.2}$ alloys [2P, 5P, 7P, 11P, 20P, 22P, 34P].

Diffusion coefficients

Work in this area includes measurement and prediction. The former includes the observations on the diffusion of napthalene into air, carbon dioxide into water and viscous and non-Newtonian fluids and hydrocarbons in zeolites [36P, 37P, 39P]. The latter deals with the theory of hydrocarbon diffusion in zeolites, polymer/solvent diffusion, and obtaining binary diffusivities from pure component surface diffusion [35P, 38P, 40P].

Viscosity/surface tension

This year's viscosity papers are exclusively predictive, dealing with liquid hydrocarbon mixtures, mixing rules for bitumens saturated with pure gases, conventional petroleum liquid and a statistical thermodynamical model for pure liquids and liquid mixtures and the influence of surface viscosity on coating flows [41P–43P].

Thermodynamic data

Equation of state studies include a modified Redlich–Kwong form for phase equilibrium and enthalpy calculations, the influence of shape and density on equations for chain molecules, and a soft sphere model for describing molten FLIBE salt [47P, 48P, 57P]. Specific equations describe carbon dioxide and argon behavior in the critical region, empirical representation of saturated steam properties, estimating hydrocarbon critical properties from vapour pressure and liquid densities, and a correlation of saturated liquid densities [44P, 49P, 60P, 62P]. Mixing rules for cubic equations of state are considered in refs. [53P, 64P]. Specific mixtures considered are: propane–methanol and 17-butane–methanol, water–H_2SO_4, polyatomic–noble gas binary mixture, helium–nitrogen, nitrogen–helium, and refrigerant mixtures [45P, 50P, 55P, 58P, 59P, 63P]. Several papers treat the heat capacity (*Cp*) and related properties. Noteworthy among them are: the study of the ability of generalized equations of state to predict gas-phase heat capacity, computer calculations of heat capacity of natural gases and new equations for calculating vapor pressure and enthalpy of aqueous lithium bromide solutions [46P, 51P, 52P, 54P, 56P, 61P].

HEAT TRANSFER APPLICATIONS — HEAT PIPES AND HEAT EXCHANGERS

A large number of papers describe advances in various aspects of heat exchanger performance in an increasingly diverse field of application.

Heat pipes

Frozen start-up behavior is analyzed for both low and high temperature designs as is the influence of grooved evaporator walls. Other efforts consider physical models for analyzing dynamic heat transfer features, analysis of flow and heat transfer for a flat-plate design and the influence of acceleration and liquid slug presence. A number of works focus on small and micro heat pipes, and the influence of rotation, thin walls and surface nonisothermicity. Cryogenic applications are reported as well as transient behavior and modeling the heat pipe also finds use in rather special circumstances: hypersonic vehicle, internally cooled cutting tools, semiconductor devices and residential heat and energy storage [1Q–22Q].

Heat exchangers

Tube bundles are studied for a number of conditions: single rows of tubes in cross-flow; corridor and staggered bundles in cross-flow, turbulent flow in axially finned rod bundles and the impact of single-phase turbulent mixing in rod bundles. For plate exchangers the heat transfer is analyzed using approximate forms for the stream temperatures, correlations developed for gas–liquid two phase flow pressure drop, and heat transfer to Newtonian and non-Newtonian food fluids studies. Other works treat the mean driving force in multichannel parallel-flow, the optimal spacing of forced convection cooled parallel plates, analyze double-pipe exchangers and propose an improved scheme for finding correlations [23Q–38Q].

Compact

A number of investigations examine aspects of compact heat exchangers: experiments in reducing the size of plate-finned exchangers, heat transfer and flow friction correlations for plate-type exchangers, influence of nonideal plate contact on performance, and experiments with thin exchangers having circular, rectangular or pin-fin flow passages. The role of turbulence is studied for microchannels and for a new type of exchanger woven with threads [39Q–45Q].

Design

The design process is enhanced by a number of papers addressing aspects of exchanger design: two dimensional effects and design criteria for convective extended surfaces, setting optimum allowable pressure drops, design methodology for vertical channels, compressed air dryers with allowance for condensation, and optimal heating and cooling strategies. Also considered are the design of a gas preheater, the optimum model of a cast radiator, the salient features of energy exchange in high-temperature, coil steam generators, and a modified approach to exchanger analysis. For plate exchangers, guidelines for selecting exchanger configurations and optimal, computer aided design for knock-down exchangers are discussed [46Q–88Q].

Enhancement and extended surfaces

Work in this category is extensive with a variety of approaches taken to enhance heat transfer. Among the analytical works a number deal with finned tubes involving spray-cooling, longitudinal conduction, petal-shaped fins, non-symmetric fins, offset fins, effects of fin thickness, inner fins, and improving efficiency by increasing finning area. Others study the screen exchanger, oscillatory heat transfer in a fin assembly, the influence of fin profile shape, and the fin-tube radiator.

For plate fins consideration is given to: conjugate conduction–natural convection, performance prediction in multistream exchangers, longitudinal flow around platens with longitudinal fins and finned tubular/plate-type surfaces.

For extended surfaces there is a review of the literature on pure convective transfer to the surroundings, spiral and double spiral exchangers, bayonet exchangers and heat transfer/fluid friction predictions for louver-type exchangers. Compressor plant exchangers, cooling equipment and the relationship between heat transfer enhancement and process integration are dealt with specifically. Also considered are: noncircular duct exchanger arrays and rod-bundles-staggered and moving.

Experimental works embrace a number of configurations: local heat transfer and flux distribution in finned tube exchangers, corrugated plate fin-and-tube exchangers, staggered bundles of cross-finned tubes, air cooled forced convection, finned heat sinks, and enhancement in round tubes using inserts. Also considered are: Heat recovery from a hot-water store, plate-fin condenser-boiler for industrial use, the influence of fin parameters on radiative and convective transport from a finned heater, and the effect of cross-sectional shape on tube heat transfer.

Enhancement by plate arrangement, pulse combustion, and the use of turbulence promoters conclude the works in the category [89Q–100Q].

Fouling, deposits, surface effects

It is observed that the effects of fouling in heat exchangers can be so severe that maintenance costs outweigh energy savings. A number of studies examine this phenomenon and its implications: A probabilistic approach characterizes fouling processes and heat exchanger maintenance strategies, the thermal resistance of heat exchanger deposits is examined, and, interestingly, mechanisms by which fouling can increase heat transfer coefficients. Another cluster of papers deals with specific aspects of the problem: contact resistance, biofouling counter-measures and fouling with specific fluids — olefin–kerosene mixtures, crude oil, and/or desalination water [101Q–110Q].

Packed beds

Packed and fluidized beds are studied for temperature distribution near a wall, air–water counter-flow through short multitube geometries, the NTU method for design of liquid desiccant dehumidifiers, and cooling tower applications [111Q–114Q].

Regenerators and rotary devices

For two-fluid recuperators, several of the methods currently available are summarized and applied to the analysis of 18 new flow arrangements. Other analytical approaches provide a solution for the parallel-flow regenerator, asymptotic periodic solutions using matrix methods and the effect of wall conduction on exchanger performance. Performance of screen stacks (500 mesh) has been investigated as well as a selection method for minimum core volume in gas turbine regenerators, and optimum energy recovery from combustion exhausts. Also noted are the application of regenerators to diving operations and the study of commercial regenerator packing behavior [115Q–123Q].

Shell and tube exchangers

Here efforts examine the influence of baffles on the mean temperature and efficiency of multipass units, the weak coupling between geometry and heat transfer for exchanger optimization, the effect of heat transfer between shell-side fluid and surroundings, unbalanced passes, and latent heat storage [124Q–128Q].

Transient

Several papers address transient behavior in exchangers. These include multipass shell and tube units, internal surface transfer coefficient in a two-phase exchanger, step response of the cross flow exchanger, and the response of parallel and counter flow exchanger [129Q–134Q].

Miscellaneous

These papers include applications, often novel or specialized, not considered in previous sections. Thus wind evaporator heat pumps, exchanger heat transfer in the presence of particulates, the effect of tube layer gap on performance, low-temperature, liquid helium exchangers, and the economic optimization of exchanger are all considered. Novel applications include a scraped-surface exchanger, liquid metal units, cooling panels, application of vortex tube in chemical analysis, plastic exchangers, and the heat exchanger network [135Q–155Q].

HEAT TRANSFER APPLICATIONS — GENERAL

Two papers [1S, 2S] provide information on the history of heat transfer and on the characteristics of viscoelastic fluids.

Aerospace

Cooling of scramjets [8S], chemistry of reentry [3S, 4S, 7S], thermal modeling [6B], and cooling of objects in space [7S, 9S] are discussed. An arc heater nozzle was tested [5S] with hydrogen combustion products.

Bioengineering

Fluid flow and heat transfer in biosystems [12S, 17S, 20S], trauma [18S], hyperthermia [13S], the bioheat transfer equation [11S] were topics of interest. The effect of clothing [15S], sterilization and storage [14S, 16S, 19S] were discussed. The thermal aspects of the manufacture of prosthetic casts are investigated [10S].

Digital data processing, electronics

Cooling methods of electronic components and modules include air [39S], liquid [34S], laminar and mixed convection [38S], two-phase flow and boiling [31S, 37S], cryogenics [24S], and flow oscillations [27S], heat transfer enhancement [21S].

Several papers cover analysis, computation, modeling, and design [32S, 33S, 35S, 36S, 40S]. The adiabatic transfer coefficient and a superposition kernel [22S, 23S] are useful concepts.

Problems in manufacturing [28S, 30S, 41S] and cooling of special devices [25S, 26S, 29S] found attention.

Energy

Various types of boilers [66S, 74S, 85S], biomass reactors [68S], cooling towers [64S] and heat shields [47S] are investigated in the literature. Analysis and experiments probe the temperatures and heat transfer in piston engines [52S, 82S, 86S, 89S]. The processes in a Sterling engine [80S] are sketched. Flow and heat transfer are probed in the nozzles [43S], cavities [65S], and labyrinths [95S] of gas turbines.

In the field of nuclear reactors, attention was directed towards design and operating problems of various reactor types [56S, 62S, 73S, 78S, 79S, 81S, 90S, 96S], towards accident prevention [69S, 93S], waste storage [75S], thermonuclear reactors [54S, 63S, 77S], the Tokamak [72S], and superconducting magnets [67S, 102S].

Optimization and application of heat pumps [84S, 99S, 101S] are discussed.

Various types of refrigerators [45S, 60S, 94S, 100S], geothermal refrigeration [97S] and organic heat carriers [83S] were discussed.

In cryogenics, attention was directed toward helium refrigerators [50S], superconduction [51S, 53S, 57S, 59S, 61S, 98S], cooling of magnets [91S], product storage [55S], and cryosurgery [46S].

Heat and mass transfer in fuel cells [42S, 58S], in a laserdisk amplifier [76S, 87S], in a solar concentrator [88S], in high pressure discharge lamps [48S, 49S], was reported. Experiments describe the characteristics of thermosyphons [44S, 71S, 92S]. Heat transfer plays a vital role at high voltage electrical power lines [70S].

Environment

Analytical models and methods to determine heat transfer and heat storage in buildings have been offered [103S, 107S, 111S, 117S, 118S, 119S, 123S, 127S]. An experimental house was subjected to extensive testing [120S]. The air flow through buildings was clarified [104S, 109S, 112S, 122S]. Geothermy can be utilized for heating of buildings [114S]. Human shape factors are offered for the thermal analysis in a radiation environment [113S]. R factors are estimated for thermal resistance analysis of reflective insulation of agricultural buildings [121S].

The thermal environment is studied on paved outdoor environments [125S], in wells [110S], in oil wells [106S], and in the deep ocean [126S]. Geothermal energy use is evaluated in Mexico [116S, 124S]. Design analysis is required for structures exposed to fires [105S, 108S]. The greenhouse effect is re-examined [115S].

Manufacturing

The papers in this field consider manufacturing processes such as welding [147S, 166S], casting [128S, 131S, 132S, 138S, 141S, 144S, 159S, 160S, 161S, 163S, 164S, 167S], quenching [158S], hot rolling [133S, 146S], grinding [140S, 153S, 155S], and machining [137S, 150S]. Thermal radiation governs the substrate temperature at the sputtering deposition of superconducting films [135S]. A solution is offered for the analysis of viscous sintering processes [165S] and metal or laser forming is discussed [145S, 149S]. Polymers are processed by extruding [139S], molding [143S] and curing [129S]. Heat and moisture transfer is modeled for food processing [136S, 142S, 157S]. The manufacture of carbon fibers [134S], particles [151S, 156S], diamond coatings [148S, 162S], iron oxide deposits [152S] is discussed. Pyroelectric distributions in ferroelectric materials are probed by thermal waves [154S]. Most of the power input to loudspeakers is converted to heat [130S].

Processing

Papers on stirred tank reactors [169S, 170S], bubble combustion reactors [184S], thermal reactors [177S], reactors for incineration [174S] and for waste treatment [179S] can be found in this year's literature. Computer modeling was applied to furnaces [180S, 196S], coke oven batteries [175S] and roasters [192S], temperature control systems [172S] are included. Coating and heat treatment of a vortex amplifier [193S] and the smelting process [182S], found attention. The thermal conductivity of liquid slags was measured [186S].

Multi-stage flash evaporators [187S], batch processors [188S], retort sterilizers [197S], and batch crystallizers [176S] pose thermal problems. Electric energy is used in electron beam processing [194S] and in separation [190S]. The differential equations describing fluid flow, heat transfer, and electric fields are used to analyze the process in a glass-melting furnace [173S], to study heat transfer from fibers in a melt-spinning process [178S], and for the control of the cure of thermosets [171S]. The effect of heat transfer intensifiers [189S] was measured and particle deposition [185S] was analyzed. Heat treatment of superalloys [191S] was modeled. Maximum heat recovery in process plants [168S] between areas of integrity can be achieved. Simplified approaches to the calculation of heat recovery in chemical systems [181S] and of the thermal behavior of Dewar cell calorimeters [195S] have been reported. A method is presented which supplies the physical parameters for the numerical simulation of hot forming processes [183S] and calculations provide the heating and cooling rate as well as the lethality in a water cascade retort.

SOLAR ENERGY

Interest and activity continue at a high level as evidenced by a doubling of the number of papers reviewed compared to a year ago.

Buildings and enclosed spaces

Various aspects of utilizing solar energy to create a controlled environment within an enclosed space are investigated. Noteworthy among these efforts are studies of the influence of exterior surface color, surrounding vegetation, transparent insulation, energy storage and operating strategies. Computer analysis id employed in design, as an element of thermal comfort control, in transwall modelling and for predicting system performance [1T–21T].

Collectors

A wide spectrum of studies explores factors influencing collector design and operation. These include materials, shielding surfaces, coatings, orientation (stationary collectors), surface geometry, direct-absorption fluidized bed receivers and the coupling of collectors with energy transport and storage. Analysis yields insights about performance, optical properties of concentrators, heat transfer within the collector and parametric studies [22T–58T].

Radiation characteristics and related effects

Efforts continue to obtain site specific data on solar radiation, direct and diffuse, to compare annual global irradiation from ground-based measurements with METEOSAT images and to construct useful models for generating synthetic hourly radiation. Polymer coatings are examined for their energy conservation possibilities. A number of papers are concerned with radiation instrumentation and measurement procedures [59T–95T].

Solar heaters, cookers and dryers

The use of solar water and solar air heaters continues to expand, including hybrid air-to-water heaters of different design. At high temperatures, in addition to ovens and furnaces, directly absorbed, concentrated radiation is applied to chemical reactors for methane reforming, methanol synthesis and solid–gas thermochemical reactions. In other works solar steam generation is employed to meet local needs [96T–130T].

Stills/Desalination

Multiwick solar stills receive study by several groups including experimental studies and analysis for performance and modelling. Desalination plant operating parameters are optimized and the use of earth-water stills examined for desalinating groundwater [131T–145T].

Heat pump-power systems

Heat pump systems are considered for their heating and cooling capabilities, the design and optimization of such systems and their simulation and analysis. Power systems include a solar source for operating gas cycles (Stirling, Ericsson, Brayton) as well as thermophotovoltaic cells and semiconductors. Applications pertain to low cost electric power production and power modules for space applications [146T–175T].

Storage/Distribution

A number of papers examine factors which bear upon the efficiency of storage or transport. Included is a comparative study of insulating materials or schemes, the efficacy of energy storage mediums, and design of seasonal storage for solar heating systems [176T–184T].

Solar ponds

The effectiveness of these systems is improved by a series of investigations: using pressure-retarded osmosis, understanding the role of convection, floating pool covers, and using porous media [185T–194T].

Heat pipes

These devices are examined in relation to solar energy collection. Of particular interest is an open-loop solar chemical heat pipe used in oil-shale gasification [195T–200T].

PLASMA HEAT TRANSFER AND MAGNETOHYDRODYNAMICS

Publications describing models of plasmas were predominantly derived for specific configurations. A model of the entire free burning arc including both electrodes, however neglecting the non-equilibrium space charge region in front of the cathode is described in several publications [13U, 18U]. A method was developed for calculating numerically the heat transfer and the electric and magnetic fields in high power arc furnaces [3U]. Wall stabilized arcs were modeled for high enthalpy plasma flow generation with an improved model for radiation heat transfer [14U], and with emphasis on calculating the change in friction factor for stable and unstable laminar and for turbulent arcs [11U]. An analytic technique for describing a stationary, cylindrically symmetric arc column with approximate expressions for the temperature dependence of the properties was developed [2U], and a new turbulence model is described for an arc in axial flow in which turbulence is initiated by local chaotic overheating of the plasma [10U]. The influence of convective effects on the power factor in ac arcs was studied including its dependence on the power frequency [17U]. The time dependent characteristics of a circuit interrupter arc in supersonic flow was modeled including the time varying electric fields during the extinction process [7U]. A new computational approach for describing chemically reacting, non-equilibrium plasma jets was developed [16U]; the transient compressible Navier–Stokes equations were solved and turbulence is represented by a k–e model. Non-steady, laminar plasma jets were modeled in ref. [5U] by numerically solving the Navier–Stokes equations. An analytic solution was derived for a one-dimensional hydrodynamic two-fluid model for vacuum arc plasmas [9U], and a three fluid transport model using a particle-in-cell approach was developed for rf glow discharges [12U]. Other models of low pressure plasmas include a new method for calculating the time varying properties of an rf discharge [8U], and the influence of recombination radiation on the heat transfer in a laminar boundary layer [6U].

Non-LTE effects in radiative transfer were described in a new model for the interaction of charged particles [4U], and the same objective was pursued in the development of a collisional–radiative model for radiative transport in low pressure He microwave discharges [1U], and more generally for line transfer considering the coupling with the ions [15U].

Models of plasma–wall and plasma–particle interactions

The heating of the substrate during vacuum arc deposition was modeled [31U], and the dominance of radiation and convection in the heat transfer from a plasma to a plastic was shown [28U]. A new formula was developed for describing the cathode voltage drop dependence on the cathode material properties [29U].

An extensive investigation of the heat transfer to spherical, non-spherical, conducting and insulating, and thermionically emitting particles in rarified plasma flows was published in several articles describing different approaches [20U, 21U, 22U, 23U, 24U, 25U, 26U]. The difference in the floating potential distribution on a metallic and on a non-metallic particle exposed to a highly ionized plasma was shown to lead to stronger thermophoretic forces acting on the non-metallic particle [19U]. The modeling results of the heat transfer to polymer particles in a plasma jet were compared with experimentally determined melting rates [27U], and the surface decomposition of polymer particles was modeled [30U].

Plasma properties

Thermodynamic and transport properties for Ar–H_2 and Ar–He mixtures were calculated [35U], and the influence of different electron energy distributions on the reaction rates and transport coefficients in non-equilibrium plasmas was determined [32U]. A critical evaluation of the low energy electron cross-sections used for modeling plasma processes is presented in refs. [33U, 34U].

Diagnostics

Laser absorption profiling of Ar lines was used to derive population temperatures, and comparison with LTE values suggest suprathermal electron densities [37U]. A supersonic nitrogen plasma flow was characterized by emission spectroscopy and laser induced fluorescence (LIF) [40U], and another spectroscopic analysis of a supersonic Ar–H_2 plasma jet involving Stark broadening, absolute continuum intensity, and relative line intensity measurements of several lines led to conclusions that LTE was present at 100 kPa and at 53 kPa, but that deviations from LTE were seen at lower pressures [52U]. In another spectroscopic characterization of a supersonic nitrogen jet used for space reentry simulation, temperatures were derived from measurements of the rotational bands [39U]. The usefulness of Raleigh scattering measurements for temperature determination was found to be limited to plasma temperatures below 9000 K in Ar or 11 000 K in He due to the dominance of Thomson scattering above this temperature [50U]. Self-reversed VUV and IR spectral lines were used to characterize a wall stabilized arc in argon, nitrogen and oxygen [53U, 54U]. Self-reversal of spectral lines was also used to demonstrate the non-LTE conditions in a mercury arc [45U]. Time resolved emission spectroscopic measurements were used to derive argon plasma jet velocities from the propagation of intensity fluctuations [41U], and a new method was developed for plasma jet velocity determination involving the application of a magnetic field and the measurement of the induced electric field with potential probes [55U]. Spectral analysis of optically thick oxygen lines was used to characterize an ablation stabilized arc in ice [38U]. A model of the IR radiation from an arc plasma showed that electron densities can be determined from radiation measurements in the 3–15 μm range [51U]. Emission coefficients for the free-free continuum of a weakly non-ideal argon plasma were calculated using a new approach involving different interaction potentials [47U]. Laser absorption measurements on cathode spot plasmas with high temporal and spatial resolution yielded data for plasma density and current density in the spot [36U]. A technique was developed for measuring the current distribution in a rail gun arc using magnetic probes [44U]. A new Langmuir probe system was developed with high time response for electron temperature and density measurements in rf plasmas [48U], and Langmuir probe techniques were also used to characterize the arc jet in a low pressure space simulation environment [43U], and in a high current vacuum arc [49U]. A new method was developed to measure particle velocities and temperatures in a plasma spray jet using time resolved pyrometry and spatial filtering with four slits [46U]. Measurements of the heat transfer to metallic spheres and small particles in a plasma jet are described in ref. [42U].

Application specific developments

The suppression of arc instabilities in a laboratory scale arc furnace by use of magnetic fields was demonstrated [57U]. The heat flux to the anode of a MPD thruster operating at power levels between 340 kW and 6 MW was determined by using thermocouples imbedded in the anode material, and by measuring the current density in front of the anode [58U]. Heat transfer measurements were performed in a 1.5 MW plasma reactor with three plasma jets designed for Ti powder treatment [62U]. A new plasma reactor design is described for synthesis of spinel powders using a counterflow arrangement to mix a liquid spray of reactants with the plasma [63U]. Another development for synthesis of ceramic powders consisted of a wall constricted arc heater [65U]. A plasma torch was developed that provides heat fluxes of about 10^4 W mm^{-2} for materials processing such as cutting of steel [59U], and new technique was developed for estimating the heat flux from the arc to the metal during plasma cutting relying on limited information of experimental parameters [60U]. Comparison of measurements of heat fluxes from a plasma jet to a quartz plate with the results of heat transfer calculations yielded quartz evaporation rates [67U]. The cooling rate of plasma sprayed Mo particles at the instant of impact on the substrate has been measured using fast two-color pyrometry, and an increase in cooling rate with coating thickness has been found [61U]. Also for plasma spraying was the development of a model describing the time dependent temperature distribution in the coating and in the substrate during the spray process, and the agreement of the results with temperature measurements served as an encouragement to proceed with the development of a thermal stress model [56U]. The error caused by neglecting radiative heat transfer in the determination of the thermal diffusivity of plasma sprayed semitransparent ceramic coatings is discussed [64U]. Two different modeling approaches for describing the synthesis of NO and the decomposition of CO_2 were compared with experimental results, and the need for obtaining accurate two-dimensional temperature profiles was established for modeling the NO synthesis [66U].

MAGNETOHYDRODYNAMICS

Models

There has again been considerable activity in the area of MHD modeling both for new solution methods for MHD equations and for specific applications. A review of 3-D models for coupled problems is presented [92U], and a new calculation procedure using a multigrid finite difference approach is described in ref. [75U]. Analytical solutions are presented for axisymmetric, stationary incompressible flows [71U] where the adaptation of a suitable reference system has led to self-similar behavior of the flow and magnetic surfaces, and for two-phase flow in a horizontal channel [90U] with two incompressible, inmiscible and electrically conducting fluids. Similarity solutions have also been derived for the thermal boundary layer for unsteady incompressible free convection MHD flows [101U], and the types of magnetic fields for which such similarity solutions are possible is derived in [70U]. In ref. [81U] it is shown that specific analytical solutions of MHD equations do not display the same symmetry properties as the differential equations, and appropriate means for making the solutions more general are given. Inconsistency between theoretical predictions and experimental results is associated with the use of "no slip" and "no spin" boundary conditions, and alternatives are suggested [88U]. The specific flow condition of low magnetic Reynolds number turbulent flow evolving from a three-dimensional state into a nearly two-dimensional stationary state is studied in ref. [97U], and numerical solutions are presented for turbulent non-isothermal flow of a conducting fluid in a vertical channel [105U]. The effect of a constnat magnetic field on buoyancy and capillary forces under low-gravity conditions has been calculated [72U]. The plane flow of a non-Newtonian fluid is described by use of complex variables [98U]. The propagation of electro-magneto-thermal plane waves in an infinite visco-elastic medium is investigated using dynamic thermo-elasticity theory [96U], and the generation of travelling waves for oblique fields is shown in [93U]. Other descriptions of instabilities include studies of the effect of an axial magnetic field on cylindrical bridges of a liquid with negligible viscosity and resistivity [99U], and on the cylindrical vapor–liquid interface [78U]. The arc formation in MHD channels has been investigated in refs. [86U, 102U].

Models for MHD generators are described using two-dimensional steady state [74U] and quasi-one-dimensional time dependent analyses [91U]. Calculation of the non-stationary turbulent two-phase flow in a Faraday generator is presented in ref. [69U], and the effect of the fineness of the powder fuel on the plasma properties is predicted in ref. [77U].

Numerous calculations deal with MHD effects in specific configurations, such as the convective boundary layer on a hot wall as encountered in nuclear reactor cooling situations [85U]. The oscillatory flow past a uniformly moving, infinite vertical plate has been analysed [68U], as has been the steady flow over a semi-infinite vertical plate with constant heat flux [82U]. The flow past an inclined plane has been analysed using a hodograph transformation technique [76U]. MHD flow of a fluid squeezed between two disks and the effect of an applied magnetic field on the heat transfer has been studied [84U], and the flow of a micropolar fluid is calculated between two infinite parallel, non-coaxially rotating disks [89U]. Analytical solutions are proposed for the effect of a transverse magnetic field on the buoyancy driven convection in a rectangular enclosure [80U]. A heat exchanger with a magnetic fluid is modeled by calculating the heat transfer from a heated cylindrical tube wall to the fluid in it [104U], and the steady state laminar flow around a circular cylinder with a magnetic field is presented in ref. [94U]. A liquid metal cooling system for fusion reactors has been modeled by considering the flow through a manifold with strong magnetic fields [95U], and the flow and heat transfer in strong co-planar magnetic fields in liquid metal films used for film cooling of diverter plates is presented in ref. [79U]. The liquid metal film formed at the tip of generator brushes is modeled by considering Couette flow with a two-dimensional periodic static surface and a transverse magnetic field [73U]. The motion of the liquid metal in a crystallizing ingot due to an a.c. magnetic field and the influence of the field on the crystallization front has been modeled [83U]. Re-entry conditions are simulated by considering the laminar, unsteady compressible boundary layer flow at the stagnation point of a blunt body with vectored mass transfer and an applied magnetic field [100U]. The effect of electromagnetic body forces on the hydrodynamic pattern of flow around bodies with internal sources of electro-magnetic fields is an important consideration for magnetohydrodynamic ship propulsion and is discussed in ref. [103U]. The free convective flow in a porous medium with a magnetic field as seen in geophysical situations is described in ref. [87U].

Experiments

A review of recent developments in magnetic fluid experiments stresses measurement techniques and two-phase flows [111U]. Several papers present experimental results of heat transfer measurements with liquid metal flows, including the flow of liquid sodium in a tube with a transverse magnetic field [108U], turbulent flow of mercury in longitudinal fields considering thermogravitational effects [112U], and the transient response of liquid gallium in a cube with a heated and a cooled wall opposed to each other for different directions of the magnetic field [115U]. The hydraulic resistance of a eutectic mixture of lead and bismuth due to a transverse magnetic field has been determined [109U, 114U], and a reduction in pressure drop due to oxidation of the channel walls has been found [109U]. A study of the motion of a magnetic fluid inside a cylinder and in the gap between co-axial cylinders due to a rotating magnetic field is presented in ref. [113U]. The use of various magnetic field configurations for the most effective stirring of the molten metal in arc furnaces has been studied [107U].

The effect of electric field on the heat transfer from a current carrying wire to a dielectric fluid has been measured [110U], and flow visualization has been used to determine the electrohydrodynamic deformation in continuous flow electrophoresis [106U].

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BOUNDARY LAYERS AND EXTERNAL FLOWS

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CHANGE OF PHASE — CONDENSATION

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HEAT TRANSFER APPLICATIONS — HEAT PIPES AND HEAT EXCHANGERS

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