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Heat transfer—a review of 1991 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 1991. 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 1991 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 1991 International Seminar on *Heat and Mass Transfer in Porous Media* was sponsored by the International Center for Heat and Mass Transfer on 20–24 May at Dubrovnik, Yugoslavia. The majority of the papers are available at the Center in a bound volume. The *ASME Turbo Expo—Land, Sea, and Air* sponsored by the International Gas Turbine Institute and held on 3–6 June at Orlando, Florida included in its program session on ceramic technology, film cooling, coatings and composites. Printed papers are available through the ASME order department. The *ACHEMA 91*, International Meeting on Chemical Engineering and Biotechnology, connecting with a large exhibition, was held at Frankfurt/Main, Germany on 9–15 June. The *Second World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics* was organized by its assembly on 23–28 June at Dubrovnik, Yugoslavia in 10 keynote lectures, 7 panel discussions, 25 invited lectures, 209 contributed papers and open forum sessions. Papers are available at Elsevier Science Publishing Co. Raymond Viscanta was awarded the first Nusselt–Reynolds Prize. The *26th Thermophysics Conference* was organized by the American Institute of Aeronautics and Astronautics on 24–27 June in Honolulu, Hawaii with sessions on spacecraft coatings, solidification and convection, thermal analysis, heat pipes, and hypersonic non equilibrium flow. Conference proceedings are available and selected papers are published in AIAA journals. *The 7th International Conference on Numerical Methods in Laminar and Turbulent Flow* was sponsored by Lockheed Missile and Space Co. and by Stanford University on 15–19 July at Stanford, California. The *1st International Conference on Computational Modeling of Free and Moving Boundary Problems* was held on 2–4 July at Southampton, U.K. Proceedings are available at Computational Mechanics Publications. The *International Numerical Heat Transfer Conference and Software Show* was organized by the International Center for Heat and Mass Transfer on 22–26 July at Guilford Surrey, England. The *27th National Heat Transfer Conference and Exposition* was organized by the American Institute of Chemical Engineers at 28–31 July at Minneapolis, Minnesota in 48 sessions on high speed/high temperature flow, nuclear containment and reactor design, two-phase flow, phase change, non-Newtonian fluids, electronic packaging, geophysical media, heat pipes, fouling, fires and combustion, metals processing, cryogenics, microgravity, plasma, and fundamentals. The 1990 Max Jakob Memorial Award was presented to R. J. Goldstein and the 1990 Donald Q. Kern Award to A. E. Bergles. The Awardees presented lectures on "Buoyancy Generated Flow in Enclosed Layers" and "Heat Transfer Enhancement — The Maturing of Second-Generation Heat Transfer Technology." Papers presented at the meeting are collected in special volumes available from the ASME order department.

The International Center for Heat and Mass Transfer organized a *Symposium on Heat an Mass Transfer in Biomedical Engineering* on 2–6 September at Dubrovnik, Yugoslavia with 12 sessions and a video forum. The *1991 ASME Cogen-Turbo V* was held on 3–5 September at Budapest, Hungary, organized by the International Gas Turbine Institute. Selected papers are available in relevant ASME journals. The *1991 Yokohama International Gas Turbine Congress*, organized by the Gas Turbine Society of Japan, held on 27–31 October at Yokohama, Japan, included sessions on turbine cooling and heat transfer, ceramics, and heat exchangers. The *112th ASME Winter Annual Meeting* was held on 27–31 October at Atlanta, Georgia; included in the field of heat transfer were sessions on bio-heat and mass transfer, fluidized bed heat exchangers, micro heat and mass transfer, phase change, superconductivity, manufacturing processes, spray systems, cryogenics, fire and combustion, heat exchangers in transportation systems, multiphase transport in porous media, nuclear reactors, and plasmas.

The *11th ABCM Mechanical Engineering Conference* held on 11–13 December at Sao Paulo, Brazil devoted one fourth of its sessions to heat transfer and thermal energy.

A list of books related to heat transfer and new journals published during 1991 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
Heat transfer in porous media, DP
Experimental techniques and instrumentation, E
Natural convection — internal flows, F
Natural convection — external flows, FF
Convection from rotating surfaces, G
Combined heat and mass transfer, H
Change of phase — boiling, J
Change of phase — condensation, JJ
Change of phase — freezing and melting, JM
Radiation in participating media and surface radiation, K
Numerical methods, N
Transport properties, P
Heat transfer applications — heat pipes and heat exchangers, Q
Heat transfer applications — general, S
Solar energy, T
Plasma heat transfer and MHD, U.

CONDUCTION

The mode of conduction which is fundamental in heat transfer encompasses a wide variety of issues in engineering applications. This past year, numerous papers dealing with theoretical, analytical/numerical, and experimental studies have been attempted for a variety of scenarios. The various sub-categories for this section on conduction include: contact conduction/contact resistance; composite/layered/anisotropic media and materials; laser/pulse heating effects, propagation and shock waves; conduction heat transfer in various geometries; conduction influenced by convection; new and approximate methods, algorithms and numerical formulations; thermal-mechanical problems, inverse problems; miscellaneous conduction studies; special applications; and special experimental conduction studies. Papers dealing with each sub-category are described next.

Contact conduction/contact resistance

Papers in this subcategory involved both theoretical, numerical and experimental investigations. Included are studies involving contact resistance in a heat-sink assembly, sliding contacts, insulation materials, electrodeposition problems, contact issues in geometries, periodic contact, dissimilar metal contacts and miscellaneous studies [1A–15A].

Composites/layered and anisotropic media

Studies in this subcategory included thin film deposition on composite substrates [23A], stability of large composite semi conductors [18A], thermal response of fire exposed composites [21A], heat transfer in anisotropic media [24A], effective thermal conductivities of transversely isotropic composites [19A], thermoplastic matrix compostie filament winding and thermal conductivity of coated short-fiber composites and fibrous composites [16A, 17A, 22A], and heat flow in solid bodies including anisotropy of thermal conductivity [20A].

Laser/pulse heating, propagation and shock waves

Numerous papers encompassing the effects of laser and of pulsed sources on materials, propagation of thermal waves and shock waves due to sudden heating and the like have been investigated and appear in [25A–48A].

Heat conduction in miscellaneous geometries

Conduction heat transfer studies in fins, tubes/rods, cylinders, plates, and miscellaneous geometries are reviewed in this subcategory. The studies include investigations involving variable heat transfer coefficients, trilaminated fins, cyclic surface heating effects, optimum shape designs, and extended surfaces [49A–53A].

Conduction with convection/stratification aspects

Natural and forced convection effects in solidification processes appear in this subcategory to include laminar forced and mixed convection studies, measurement of temperature fields for conduction–convection problems, conjugate heat transfer issues, laminar tube flow coating of moving surfaces, and comparative experimental and numerical studies [54A–62A].

Methods and approaches/numerical studies

As always, there is a wealth of information involving studies attempting to employ new and alternate methods, algorithms and numerical studies in conduction problems. Attempts to include comparative experimental and numerical studies are also included. These papers appear in [63A–104A].

Thermal-mechanical problems

Interdisciplinary thermal-structural problems have always been an important issue in the design of engineering components and structures. Thermal-stresses induced due to various heat loading scenarios have been investigated in both isotropic and composite material. These appear in [105A–124A].

Inverse problems

In comparison to direct strategies for the solution of temperature fields and the like, inverse formulations have received increased attention in recent years. Various studies involved in this subcategory include multi-parameter inverse problems, measurement of heat transfer coefficients, inverse convolution methods and inverse solutions for unsteady problems [125A–128A].

Miscellaneous conduction studies

Numerous other related studies involving conduction have also been attempted for a wide variety of problems. These appear in [129A–141A].

Special applications

Particularly unique or special applications are grouped in this subcategory. Several of these studies often are not restricted to conventional heat transfer problems traditionally encountered. These papers appear in [142A–189A].

Special experimental conduction studies

Papers in this subcategory include applications of experimental techniques to clothing, finned tubes, heat-conducting materials, magnetic refrigerators, conducting/radiating films, influence of ultrasonic effects, and mechanisms of heat transfer augmentation involving conduction [190A–202A].

BOUNDARY LAYERS AND EXTERNAL FLOWS

The research on boundary layers and external flows during 1991 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 and flows with special fluid types.

External effects

Several papers documented the effects of buoyancy, imposed vibration, external disturbance level, impinging wakes, disturbance fields induced by a nearby cylinder and by large eddy breakup devices. Several documented the responses of boundary layers to pressure gradients and curvature. Results of several entries showed effects of embedded vortices, magnetic fields and bubbling jets on boundary layer heat transfer; two discussed boundary layer flow with conjugate heat transfer [1B–22B].

Geometric effect

Papers in this category focus on special effects due to global or surface geometry. Several were for cylinders, cones and other geometries with stagnation flows and cylinders at various orientations to the flow. Other geometries include plates of finite thickness, wall jets, curved hills, swirling cavity flows, planetary flows and heat transfer with short heating lengths. Wall geometries include semi-permeable walls, permeable walls and rough walls. A study was presented for the particular geometry of a mechanical face seal [23B–43B].

Compressibility and high-speed flow effects

High Mach number flows were investigated for a cold-plate, a plate at an angle of incidence, blunt bodies, an aeroassist experiment and reentry vehicles. The effect of heat transfer on boundary layer stability was analyzed [44B–53B].

Analysis and modeling

Analytical papers include application of integral techniques, the development of a complete turbulent velocity profile for non-Newtonian fluids, an estimation of the boundary heat transfer coefficient distribution and an exact solution for convective diffusion. Experimental results were presented for spanwise eddy diffusivity. Analytical techniques include a "large vortices" model, a mixing length model for rough surfaces, analysis of chemical non-equilibrium effects, analysis of an orthotropic layer, and characterization of variable temperature effects. Several papers dealt with turbulence and transition in gas turbine blade flows [54B–66B].

Unsteady effects

Papers in this category include results of studies of wavy films, effects of large-amplitude gas oscillations, heat exchange processes with periodic intensity, modulation of combustion and the analogy between unsteady heat and mass transfer. Transient analyses were conducted for rocket nozzles, wall transfer probes and unsteady laminar boundary layers [67B–74B].

Films and interfaces

Studies of films include two papers on falling films and one on a wavy film of LiBr. One paper dealt with microconvection at an air–water interface and another discussed heat transfer processes on counter-current contact plates [75B–79B].

Fluid types

Results were presented for studies of the effects of temperature-dependent properties on the heat–mass transfer analogy, of low-conductivity fluid behavior, of the evolution of impurity distribution and of thickness scaling for boundary layer flow in 4-He films. One paper was presented for a liquid and particulate system and another presented results for a gas–particulate system [80B–85B].

CHANNEL FLOWS

Forced and mixed convective heat transfer in ducts was examined under a variety of geometries and flow conditions and was divided into the following categories: straight-walled circular and rectangular ducts; irregular geometries; entrance effects; finned and profiled ducts; flows with swirl and secondary motion; oscillatory and transient flow; two-phase flow; low-temperature applications; and miscellaneous studies including non-Newtonian flow, magnetofluid-coated channels, electro-convection, and channel/fluidized bed studies. The literature also contained a review paper [1C] highlighting the heat transfer of gas flows in channels at high heat loads.

Straight-walled circular and rectangular ducts

A variety of turbulence models were tested in the simple geometry provided by straight-walled ducts, including a low Reynolds number k–ε model, higher order Reynolds stress models, and mixing length approaches. Channel modeling was compared to experimental results and direct Navier–Stokes calculations. The majority of channel flows were examined under turbulent flow conditions, although selected laminar flow situations were studied. The following applications were treated: combusting flows; the flow of hydrocarbon fuels; wall heat generation to model the cooling of electronic equipment; channel flow drying using desiccants; and permeable wall situations [2C–24C].

Irregular geometries

The heat transfer literature examined a variety of irregular duct geometries under conditions conducive to the enhancement or reduction of the heat transfer rate [25C–49C]. Straight-walled annular ducts were studied under chemically reacting non-equilibrium conditions, for relaminarization situations in strongly heated gas flow, and for annuli with moving cores. The heat transfer of accelerating and decelerating flow fields were investigated in a number of geometries, including propulsion nozzles, convergent–divergent rectangular ducts, and for ducts with periodically varying walls. Several complex geometries were also considered, including cusp-shaped ducts, axial flow in rod-bundle clusters, and in ducts with jet crossflow injection.

Entrance effects

Many practical heat exchanger systems require efficient thermal transport before fully-developed hydrodynamic or thermal conditions can be established. There were a number of papers in the literature which examined these spatially developing fluid flow and heat transfer situations [50C–62C]. The entrance region of an annular channel was treated as a Sturm–Liouville problem. Entrance regions of trapezoidal, semi-circular, and rectangular ducts were investigated under a variety of conditions, including strong three-dimensional flow and in converging–diverging ducts. Parallel plate channel flow was studied at low Reynolds numbers and for asymmetric heating. Mixed-mode heat transfer was considered in the following situations: forced and natural convection in a semi-circular duct; axial conduction and radiation in a circular pipe; as well as conduction and convection in a circular pipe.

Finned and profiled ducts

The heat transfer augmentation due to profiled duct surfaces was an active area of research during the year [63C–94C]. Twice as many contributions were made in this subcategory in the 1991 literature, as compared to the previous three years. Furthermore, the work was approximately two-thirds experimental and one-third numerical, a trend which was also somewhat unexpected based on recent reviews showing a emphasis on numerical work. Applications most commonly encountered in the literature were for gas turbine blade cooling and the heat removal from electronic equipment. These studies included v-shaped ribs in square passageways, angled discrete ribs in rectangular channels, opposing wall roughened channels, and a number of studies of low-profile electronic components in various arrangements. The following configurations were also examined: supercritical flow with spacer elements; channel junctions with dissimilar surface roughness; a square rod in a channel; grooved channels; periodically dimpled channels; and longitudinal fins.

Duct flows with swirl and secondary motion

Secondary motion in ducts set up by the radial imbalance between momentum and pressure forces can lead to either heat transfer augmentation or a reduction in heat transfer if relaminarization is experienced. Secondary motion can also be imposed on the flow by swirl-inducing inserts called twisted tapes. The literature examined a number of flow configurations including swirl in a cyclone chamber, variable-density swirling pipe flow, flow in coils including steeply bent coils, alternating curved pipes or serpentines, and curved square ducts. Hot and cold fluid exchange was also studied in a circular duct through a process called eversion [95C–112C].

Oscillatory and transient flow

Periodically forced and transient channels flows were examined in a number of situations in the literature [113C–119C]. Oscillatory flow in a porous medium channel formed by two large parallel plates revealed a reduction in overall heat transfer rate with increasing permeability parameter. Oscillating pipe flow with applications to Stirling engine heat exchangers was studied numerically. A periodically varying inlet temperature was imposed on a fully developed Graetz problem to model the heat transfer in pulsed lasers. Transient flow was studied under a variety of conditions including: unsteady conjugate heat transfer in laminar pipe flow; unsteady flow of Freon 12 in channels to model vertical heat pipes; and a general study of the effect of changes in wall temperature, coolant flow rate, and wall heat flux on overall performance of cooling a fluid in a pipe.

Two-phase flow in ducts

Two-phase flow with applications to duct geometries is reported here as refs. [120C–128C]; a more complete examination of phase change heat transfer can be found elsewhere in this review. Film condensation heat transfer was studied under a variety of conditions including vapor condensation in parallel plate channels, droplet deposition and mist supercooling in turbulent channel flow, and in annular tubes having helically placed ribs and wires. Boiling heat transfer was investigated in a vertical channel with the upward and downward flow of fluid under constant pressure drop conditions. Other studies included air–water plug–slug flow, micro-encapsulated phase change in slurries, and gas–particle suspension flows.

Cryogenic applications

Low temperature applications included the following: the stability of superconductors cooled by He II; the theory of thermal hydraulic quenchback; the examination of radial heat transfer of He II in a diverging channel; the effect of channel geometry on heat transfer in He II; and a performance study of a superconducting generator [129C–133C].

Miscellaneous studies

There were a number of channel flow studies which did not fit well into the subcategories reviewed above [134C–155C]. Non-Newtonian flow of a viscoelastic fluid was examined between two parallel plates and non-Newtonian particle-fluid heat and mass transfer was investigated. The heat transfer and associated drag of magnetofluid-coated channels were investigated; planar and sinusoidal coatings were considered. The effect of organic liquid deposits on heat transfer in a channel was studied, as well as the downward flow of a viscous electrically conducting fluid in a magnetic field. Electroconvection due to corona discharge was also treated. Several studied examined the heat transfer in circulation systems including fluidized bed-channel arrangements and combustion chambers.

FLOW WITH SEPARATED REGIONS

Flow configurations characterized by large scale flow separation and fluid recirculation were categorized as follows: flows encountering a backward-facing step; fluid flow and heat transfer characteristics of a single circular cylinder in crossflow; multiple cylinder arrays and tube banks; flow past irregular bluff-body geometries; and a handful of studies examining flow separation in miscellaneous applications.

Flow past a backward-facing step

Numerical and experimental studies examined the fluid flow and heat transfer behavior downstream of backward-facing steps and sudden-expansion geometries [1D–7D]. Experiments in air, oil, and viscoelastic fluids were conducted; transient flow past a step was also studied in a Ludwieg tube. Various turbulence models were applied to the separated flow downstream of a step and compared to experimental data. The heat transfer characteristics downstream of a step having a cylinder positioned at the top corner were examined. Heat transfer enhancement or deterioration was possible depending on the location of the cylinder.

Flow over an isolated circular cylinder

One of the most classic flows, that of unsteady separated flow past a circular cylinder, remains an active research topic in the heat transfer community [8D–15D]. The vortex shedding phenomenon behind the cylinder is both rich in detail and fascinating to observe in the laboratory; a complete description of the flow physics will no doubt allude researchers for decades to come. A number of studies examined the influence of flow disturbances on the cylinder heat transfer characteristics; free stream turbulence, pulsation, and a tripping wire were considered. The influence of thermal boundary conditions on azimuthal heat transfer characteristics was studied, as well as the effect of thermal ratcheting. Electrostatic cooling of a cylinder was also investigated experimentally.

Multiple cylinder arrays and tube banks

The fluid flow and heat transfer characteristics of multiple-cylinder configurations are quite complex and highly dependent on cylinder geometry and arrangement. Studies in the literature covered the spectrum from complete heat exchanger arrays to fundamental work aimed at describing the fluid-thermal behavior downstream of two circular cylinders in crossflow [16D–24D]. Numerical solutions were obtained for diamond-shaped pin fins arrays; a total of 18 arrays were examined as a function of vertex angle and Reynolds number. The heat transfer in gas–solid suspensions was considered in a staggered tube array. The effect of wall roughness in circular tube arrays was investigated experimentally in air. A single cylinder placed downstream of a row of cylinders, as well as several two-cylinder arrangements were studied.

Irregular bluff-body configurations

Separated flow downstream of bluff objects can lead to either the enhancement or reduction of heat transfer depending on flow conditions and geometry. A number of irregular geometries were considered in the literature including surface-mounted protrusions, blunt flat plates, wedges, and bodies at incidence in supersonic flow [25D–36D]. The naphthalene sublimation technique was used to deduce heat transfer characteristics in the neighborhood of wall-mounted cylinders. Surface-mounted cubes, plates, and vortex generators were also employed to study wall-obstruction heat transfer behavior. Turbulence modeling schemes, in particular the k–ϵ model, were compared to experimental results for variously shaped blunt objects.

Miscellaneous studies

Flow separation and heat transfer were investigated in a number of configurations which did not fall into the categories identified above [37D–44D]. The mixing characteristics of a free turbulent jet issuing from a rectangular orifice were examined. Jet mixing in a cylindrical vessel was studied under a number of jet nozzle configurations; vortex chamber flow was also considered. Hybrid k–ϵ turbulence modeling of recirculating flow was compared to experimental results. Stagnation region flow and separated flow around accelerated/decelerated particles were also treated in the literature.

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.

Conduction

Several studies [1DP–8DP] concern the calculation of an average thermal conductivity for a porous medium. Inhomogeneities may be considered random or ordered. Cases considered include saturated packed beds and solids with small fractions of a second phase.

Packed beds (forced convection)

Many applications consider a fixed solid material where fluid is forced through it by an externally imposed pressure difference [11DP, 12DP, 14DP–17DP, 19DP, 21DP, 22DP]. Most of these studies involve experiments where the primary objective is to maximize the heat transfer while minimizing the required pressure drop. Another situation where packed beds occur is at the start-up of a fluidized bed reactor [10DP]. The possibility of phase change in the solid bed is important for thermal storage systems [9DP, 13DP, 18DP, 20DP].

Packed beds (natural and mixed convection)

Natural or free convection in packed beds was considered in several analytical or numerical studies [24DP, 26DP, 29DP, 35DP, 36DP, 45DP, 47DP, 50DP]. A few studies were directed toward finding efficient computational schemes for flow in porous media [49DP, 53DP]. Experimental studies using flow visualization were also reported [26DP, 44DP]. Anisotropy of the porous media [30DP, 42DP], non-Newtonian fluids [40DP] and radiation [25DP] were considered. Mixed free and forced convection was studied in several numerical [34DP, 37DP, 46DP, 51DP] and experimental [38DP] studies. The onset of convection and instability was the focus of other studies [28DP, 43DP, 48DP, 52DP, 54DP]. The occurrence of phase change in the packed bed was considered including liquid–gas interfaces in the fluid [23DP]. Non-Darcy effects were the object of several studies [27DP, 31DP–33DP, 39DP, 40DP, 55DP].

Fluidized beds

Fluidized beds are of great current technological interest, and a large number of articles for the current year are reported. Analytical scaling [64DP] and particle modeling studies [81DP] have been conducted, and several computer models [61DP, 62DP, 70DP] have been constructed. Many studies have focused on the heat transfer coefficient between the fluidized bed and the wall [57DP, 58DP, 59DP, 69DP, 72DP, 73DP, 75DP, 76DP, 84DP] while others have studied the heat transfer between the gas and individual particles [60DP, 77DP]. There have been studies of the heat transfer between the fluidized beds and objects inside the beds including tubes or cylinders [66DP, 67DP, 79DP], wires [74DP] and larger particles [56DP]. Other studies involved bubble formation [71DP] and interaction [78DP]. Experimental studies have considered expansion [65DP], conditions at minimum fluidization [63DP], vibrationally fluidized beds [83DP], local hydrodynamics [85DP] and the relationship between particle motion and heat transfer [68DP]. Two studies were done in the related area of heat transfer to slurries of particles [80DP, 82DP].

Heat transfer combined with mass transfer or chemical reactions

Numerous studies were done of combined heat and mass transfer in porous media. Models and numerical results for non-reacting systems concerned coupled heat and mass transfer in differing configurations [89DP, 90DP, 93DP, 96DP-98DP]. Specifically, the effect of Hall current and wall temperature oscillations for rotating porous media [88DP], steam–water counterflow [102DP] and sublimation cooling [101DP] were considered. Two papers reported experimental results [91DP, 103DP]. Analysis and numerical results for heat transfer in chemically reacting systems of porous media were also reported [86DP, 87DP, 92DP, 94DP, 95DP, 99DP, 100DP].

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. Fixed beds are analyzed in the context of dehumidification [131DP], solid rocket propulsion [136DP], oxidation of methane [123DP], ammonia synthesis [109DP], coke ovens [122DP], regenerators [132DP] and *in situ* vitrification of hazardous waste [107DP]. One study suggests capillary-porous powdered material as an improved porous media [135DP], another considers regeneration strategies for catalysts [132DP] and a third considers the migration of moisture in building materials [114DP]. The largest number of papers addressed the problem of the drying of materials, a fixed bed problem involving combined heat and mass transfer [108DP, 111DP, 113DP, 117DP, 120 DP, 121DP, 124DP, 126DP–130DP]. Studies concerning specific applications of fluidized beds also included drying [112DP], combustion of coal [104DP, 119DP, 133DP], avoidance of frosting in heat pumps [137DP], freezing of food [116DP], low temperature thermal storage [115DP], incineration of organic waste [134DP] and fluidized bed nuclear reactors [106DP]. Many studies addressed the problems of heat and mass transfer in soils including the migration of water and nutrients [105DP, 110DP, 138DP] as well as soil testing in an ion-exchange resin [139DP]. Environmental applications include models of heat transfer in sedimented lake bottoms [118DP] and heat and mass transfer in root systems [125DP].

EXPERIMENTAL METHODS

Temperature

Several papers described new temperature sensor designs or quantified the performance of existing sensors. A fast-response temperature sensor for measuring atmospheric temperature was described [9E]. By decreasing the time constant by a factor of five the radiation error was increased by a factor of two. An in-process workpiece temperature sensor was described that could be used to measure the real-time temperature of a workpiece to prevent thermal damage [1E]. The bias error associated with a thermocouple located close to a wall was estimated by analyzing the conjugate heat transfer in a body whose surface temperature is being measured [8E]. The resistance–temperature characteristics, self heating effect and stability of a new type of encapsulated rhodium–iron resistance thermometer were studied [4E]. The thermal–electric force generated across a specimen due to a small change in the surface temperature is used to follow phase transitions within the specimen [6E]. This technique can also be used to precisely calibrate the temperature sensing element when the transition temperature is known. The thermodynamic behavior of a self-calibrating thermocouple is simulated [7E]. The model includes the effects of the junction location and the mass and heat of fusion of the encapsulated metal. The effects of parameter changes on the response of a thermocouple used in a vacuum environment were simulated [3E]. Temperature measurements of a thin film of aluminum have been made using ion beam bombardment from 100 keV argon ions [10E]. A multi-bit optical sensor multiplexing and networking concept is presented in which the accuracy of the data is not necessarily high but a large number of sensors are to be monitored [5E]. Internal temperature distributions within a solid can be determined from surface temperature measurements [2E].

Heat flux

Several papers reported experimental and theoretical work on the design and use of heat flux transducers [12E–14E, 16E–20E] Sensors were described to measure surface heat flux in fluidized beds [15E], on a porous surface with through flow [21E] and to measure surface shear in a blast wave [11E]. Improvements in heat flow meters used to measure the amount of energy transported in a fluid stream were given [22E, 23E]

Liquid crystals

Liquid crystals have been used to visualize the surface temperature distribution on models in subsonic and supersonic flow [27E], on flow past rough surfaces [26E], and on thin metallic foil heaters under an impinging jet [25E]. A theoretical study was conducted to determine the reorientation of liquid crystal molecules induced by laser beams [24E].

Infrared thermography

Infrared thermography has been used in a variety of applications to determine surface temperature distributions [28E–30E]. Surface temperature measurement using infrared techniques has been used to deduce the internal temperature distribution within a solid [31E].

Optical tomography

A review of axial tomography was given [34E] applied to heat transfer and fluid flow. A review of holographic interferometry was also presented [33E]. Tomographic methods were applied to measure a temperature field in a gas [35E] and a two-dimensional heat transfer coefficient distribution on a plate [32E].

Optical methods

The spherical aberration on an interferometric system was quantified when using wedge fringes [39E]. Interferometry was used to measure substrate temperature [40E]. Other optical temperature measurements include the use of coherent anti-Stokes Raman scattering [41E], Rayleigh scattering [36E], and combustion product absorption spectrum [37E]. The local convective heat transfer coefficient on a surface could be measured in a transient process using a pulse of radiant energy on the surface [38E].

Frosting

Frost density has been measured using beta-ray and gamma-ray transmission measurements [42E]. A different non-contact technique has been developed for measurement of frost formation on heat exchanger surfaces [43E].

Particles

Particle image velocimetry continues to be improved by using a two-dimensional Fourier transform analysis of the Young's fringes [45E]. A related method has been developed to measure temperature distributions in a fluid using temperature sensitive micro-encapsulated liquid crystal particles [44E].

Radiation

A fully automatic spectroradiometer has been designed to measure the absolute spectral irradiance of light sources in the 800–2400 nm spectral range [46E]. A blackbody source for use in the -50 to 200°C range has been described [50E]. Measurement of spectral emissivity [48E], broadband emissivity [47E] and total hemispherical emissivity [49E] of various materials has been reported.

Thermophysical properties

A variety of techniques have been used to measure the thermophysical properties of solids [51E, 52E, 54E, 55E, 59E, 61E, 63E, 67E] Other methods use radiant heating methods [53E, 57E, 66E]. Two publications describe the measurement of thermophysical properties of liquids [56E, 60E]. A method to reduce radiation errors [65E] and a measurement technique for porous materials [62E] have been described. A method to measure *in situ* wall-rock thermal conductivity in mines [64E] and a continuous measurement of the effective thermal conductivity of rock–water mixtures in well cuttings have been given [58E].

Hot wires

Calibration of hot wires at low velocities (15–95 cm s^{-1}) [71E], the effect of the wire length on eddy size measurements [70E], correction for measurements near a surface [74E] and the use of a flying hot wire using a four bar linkage [68E] have been described. Two methods for measurement of turbulent stresses have been presented, a rotating, slanted technique [73E] and a combined flow and temperature measurement procedure [75E]. The frequency response of cold wires has been determined in two applications [69E, 77E]. Measurement of flow direction [76E] and measurement of a small liquid flows using a transient thermal method [78E] have been reported. A long hot wire that traverses the entire wake of a cylinder has been used to measure the drag on the cylinder [72E].

Miscellaneous

A review of the naphthalene sublimation technique [87E] to model convective heat transfer was presented. An acoustic method to detect boiling is being developed [79E]. Uncertainty analyses were used to characterize a heat transfer facility [83E] and to assist in cost optimization in the design of heat transfer experiments [85E]. Nondestructive thermal testing has been used to observe material defects in petrochemical plants [84E] and defects in the layer below a surface layer in a multilayered wall [82E]. Specific applications of heat loss measurements have been made in directional solidification furnaces [80E], a thermohydraulic facility [86E] and in buildings [81E].

NATURAL CONVECTION—INTERNAL FLOWS

Buoyancy driven flows in enclosed layers continue to be of interest. A number of geometries, boundary conditions, physical phenomena, and applications attract researchers in basic and applied sciences including engineering, physics, astronomy, meteorology, and geology. For example, studies of horizontal layers heated from below provide insight into a number of problems including the evolution of flows from simple to complex forms, the development of solutions to non-linear phenomena, and important knowledge of turbulence.

Horizontal layers heated from below

For horizontal layers of fluid heated from below at low Rayleigh number questions of stability and the onset of flow have been the focus of several studies [3F, 11F, 12F, 14F, 16F, 21F]. They include the influence or non-influence of Prandtl number on the critical Rayleigh number, instability in a multi-layer system, stabilization of the flow, influence of a permeable barrier, and stability of thick layers of fluid. Post-stability studies [5F, 7F, 15F] include the effect of a number of factors on the wavelength of cells or rolls and their orientation. These include experiments in a pentagonal vessel, control of the longitudinal rolls in a rectangular duct and a feedback mechanism for suppressing the development of the flow.

Analytical and numerical studies at moderate and high Rayleigh number [1F, 9F, 10F, 13F, 17F, 19F, 23F] examine several phenomena including scaling effects, flow at moderate Rayleigh numbers to the point where chaotic convection can take place, convection in a fluid with temperature-dependent viscosity, and convection in a horizontal layer at a very low Rayleigh number. At high Rayleigh number coherent structures were sought. Another study concerns the influence of temperature varying viscosity on convection in a magnetic field. A number of other studies consider various aspects of convection in horizontal layers. These include analysis of flow in a mushy layer where local chimneys are found and in a partially filled horizontal enclosure [2F, 20F]. The influence of magnetic fields on convection in horizontal layers including those with internal heat generation and in inclined magnetic fields have been studied [6F, 18F]. The influence of spatially varying boundary temperature, internal heat sources, and vibration [4F, 8F, 22F] have been examined numerically and analytically.

Double diffusive flow

In buoyancy-induced flows variations in density may be due to concentration as well as temperature variations. Investigators considered double diffusive convection in rectangular enclosures with density differences across flint layers between vertical walls, combined experimental and numerical studies including variations with electrochemical convection and thermal buoyancy forces [25F–27F, 29F]. Convection in binary gases where Soret and Dufour effects can be important [33F–35F] has been examined numerically and experimentally. Other phenomena in double diffusive convection that have been studied [24F, 28F, 30F–32F] include asymmetric oscillations, the influence of key dimensionless parameters on steady flow phenomena, opposed flows and convection in large scale geothermal systems and combustion of aerosols.

Marangoni convection

If a free surface is present in a fluid layer or if there are overlaying layers of different fluids (fluids with different surface free-energy) then variations in surface tension across the surface can induce flow in addition to the flow due to differences in density. A number of studies have been undertaken in this area [36F–51F]. These include the influence of surface deformation on the free surface of such Marangoni or thermocapillary flows. Other studies include the influence of internal energy sources, in a single layer or at the interface between two immiscible fluids. The onset of flow and the initial flow planform have been examined analytically and experimentally. Other studies include the potential interfacial reaction, and dissipation in high Rayleigh number flows. Studies of floating zones including periodic instability and applications to crystal growth and melting problems have been presented.

Inclined layers

Unlike horizontal fluid layers, inclined layers generally do not have a critical Rayleigh number for the onset of flow. Flows in such layers are of interest in a number of applications as well as for their potential for testing of numerical codes and experimental techniques [52F–56F]. Studies include those for flow in square enclosures with internal energy sources as well as convection in inclined rectangular enclosures. Numerical experiments with convection in inclined non-rectangular enclosures and in inclined slots with a hexagonal honeycomb core have been presented. Experiments have been performed on convection in uniformly heated inclined tubes.

Vertical enclosures—differentially heated layers

Differentially heated layers have a horizontal temperature gradient impressed upon them. The flow depends strongly on the geometry (e.g. whether the layer is very shallow, something on the order of a square container, or a vertical channel).

Studies in differentially heated shallow cavities [83F, 88F, 93F] include experiments with an oscillatory flow and with liquid metals. Other studies include analysis of the convection in a Hele–Shaw cell and a shallow layer of water near its maximum density point. Many studies reported on flow in differentially heated square cavities [61F, 75F, 76F, 80F–82F, 90F]. Such geometries have been the testing ground for a number of numerical schemes for laminar flow. These include special algorithms for accurate numerical calculations, details of the flow in the corners of a cavity, studies over a large range of Rayleigh number, of transient convection with different thermal boundary conditions or lid motion on the top of the cavity. Other studies in a square cavity include the effect of discrete heat sources and porous layers as well as the influence of a cooled top and partially heated sidewall and the influence of turbulence at moderate Reynolds numbers [58F, 68F, 73F, 84F]. Three-dimensional flows in similar geometries include a numerical study for flow in a cube and experiments on transient convection in differentially heated enclosures [65F, 66F, 83F].

Flows in vertical channels (large in height compared to the spacing between the walls) have been examined [64F, 67F, 70F, 72F, 75F, 87F]. These include correlations for heat transfer, a low Rayleigh number asymptotic solution, visualization of a three-dimensional flow that can occur in such a channel, numerical analysis to include effects of potential mass transfer and experiments on channels with air, and some using laser speckle photography to indicate the temperature variations. Other studies on vertical channels [61F–63F, 69F, 88F, 94F] include the influence of variations in surface finish including wall roughness elements, partitions, internal permeable screens, as well as the effect of counter induced falling liquid film on flow and heat sources embedded in the wall. Studies on vented channels [60F, 82F, 90F, 91F] in which flow can leave the layer include numerical and experimental works, and interferometric visualization of the flow.

Numerical and experimental studies have been reported on the flow in vertical circular tubes, and coaxial cylinders [57F, 71F, 76F, 85F, 93F]. These include studies of convection in pipes at high Raleigh number, details of the flow structure and temperature distribution, the effects of thermophysical properties of the two walls as well as applications and analysis of low Rayleigh number flow in the annulus between coaxial cylinders.

Horizontal tubes and annuli

Several different geometries have been examined in the past year in terms of convection in layers between a body and a surrounding enclosure as well as heat transfer to fluids in completely enclosed cylinders and related geometries. The work on flows inside tubes includes the influence of a nonuniform distribution of temperature on the boundaries and convection to air–water layers in a horizontal cooled circular tube [98F, 102F]. Studies of flow and heat transfer in the annulus between two-horizontal circular cylinders [97F, 99F, 101F, 103F, 104F] include the prediction of instabilities in the upper region of the annulus at high Rayleigh number and numerical procedures for analyzing such flows, three-dimensional effects in relatively short annuli, influence of open ends on the annuli, measurements of flow in an annulus partially filled with liquid, and trainsient flow in an annulus.

Reports on a flow in other enclosures [95F, 96F, 100F, 105F, 106F] includes flow in cylinders containing heated octagons, heated flat plates, flow in a cube containing a heated plate and flow with enclosed inner bodies of various shapes.

Thermosyphons

In thermosyphons or natural convection loops [107F–112F] flow is generated by differences in density (usually from temperature differences) on the two opposite sides of a flow loop. These are often used in energy systems to provide a self generating and regulating flow. Applications include solar water heaters, nuclear core cooling, rotating machinery, and some geothermal processes. Correlations have been provided for such loops including feedback mechanisms. Instability experiments and analysis of cellular structure, as well as of steady flows in systems of arbitrary cross section have been reported.

Porous media

Many of the studies on flow in porous media are covered in section DP of this review. However, some of special interest to buoyancy driven flows are covered herein [113F–122F]. Studies in horizontal layers include the influence of multiple heat sources and experimental verification of the equations of motions. Through flow effects on instability and local cooling along the height of a layer have also been considered. Numerical studies have been performed on the flow in a vertical porous annulus as well as in a vertical enclosure with internal energy sources. The influence of large property variations, non-Darcian effects and applications to combustion systems have been considered.

Mixed convection

Mixed convection flow is generated by externally induced pressure differences as well as by body forces. Many works in this area are covered in section B on channel flows in this review; some [123F–136F] are covered in the present section. A number of these relate to flows in horizontal tubes or channels. These include influence of forced flow on the platform in a channel heated from below, a bifurcation in the structure of the flow in a rectangular duct, and the heat transfer in a tube with periodic heat input. Other studies consider laminar mixed convection in the entrance region of rectangular ducts and the influence of discrete heat sources as well as the influence of convection on system tubes with internal tapes. In vertical channels, prediction of the mixed flows and convection flows at supercritical pressures in both opposing and assisting flows when asymmetric heated ribs are present in the channel and transient flows have been described.

Miscellaneous

A number of other boundary conditions, special cases, and geometries have been studied [137F–155F] These include use of electrochemical techniques to study buoyancy driven convection, and cooling of protruding fins and arrays inside enclosures, with and without partitions. Still other studies examine convection in enclosures with conducting plates, flow of cryogenic suspensions, convection in enclosures with participating radiation, and magnetic effects on a paramagnetic fluid. Stratification of a cryogenic liquid, convective stability of a layer in a high-frequency vibration field and during solidification, as well as transient convection with a time-dependent body force have been described.

Applications and buoyancy driven flows

Buoyancy driven flows occur in a number of applications. Many of these are described in earlier sections of this chapter, some specific ones are described here [156F–164F]. Studies include convection in Trombe walls as used in solar collectors and in the upper region of solar ponds. Cooling of electronic components mounted on both horizontal and vertical boards have been examined. Convection in horizontal district-heating pipelines has been analyzed to optimize design considerations. Numerical studies examine stratification in thermal energy systems and experiments have been done on convective flows in hot water storage devices. Unsteady analysis has been applied to convection in chemical vapor deposition devices.

NATURAL CONVECTION — EXTERNAL FLOWS

A significant amount of work has been reported on natural convection in external flows. The work involves fundamental and applied studies, in which experimental, analytical, and/or numerical results are reported. The topics of turbulence and instability have been vigorously investigated. A number of geometries including vertical, horizontal, and inclined surfaces and cavities have been considered.

Vertical surfaces

Experimental and theoretical investigations [1FF–19FF] have been reported for natural convection on vertical surfaces such as plates, cylinders, and cones. The work includes different thermal boundary conditions and the use of suction or blowing at the plate surface. Whereas most papers deal with Newtonian fluids, some work on power-law fluids and micropolar fluids has been described. The effect of variable properties and of compressibility has been considered. Some studies include mixed convection in different configurations. Natural convection in porous media is treated in some papers. One analysis investigates natural convection on a surface covered with hair. Other special features of the reported investigations include: very high Prandtl numbers, MHD, wall plumes, and falling liquid films.

Horizontal surfaces

Natural convection from horizontal surfaces such as plates and cylinders has been studied in [20FF–31FF]. Some papers deal with multiple cylinders and the interaction of screens with horizontal surfaces. Investigations have been reported for non-Darcy flow in porous materials and for fluids described by the Ellis model. The presence of thin liquid films and film boiling on horizontal plates has been studied. Features such as composite surfaces and electric fields have also been included.

Inclined surfaces

The effect of inclination of the surface on natural convection has been considered in [32FF–38FF]. The investigations include semi-infinite and finite plates, vertical corners, and plates with finite heat sources. One analysis deals with the effect of non-uniform gravity on micropolar fluids.

Cavities

Natural convection around cavities of different geometries and orientations is the subject of a number of investigations [39FF–45FF]. The geometries include rectangular, cubic, and hemispherical cavities, backward-facing step, corners, and heated blocks mounted on plates. Mixed convection in a cavity is considered in some studies.

Instability and turbulence

An important aspect of natural convection is the instability it causes. In particular, when a fluid layer is heated from below, an unstable flow pattern is quite common. A number of investigations [46FF–65FF] have dealt with instability or turbulence in natural convection. The stability of the flow has been studied for internally heated fluid layers, mixed convection boundary layers, porous materials, and thermocapillary convection. The stability of double diffusive interfaces has been investigated. A number of papers deal with vortex flows and vortex shedding. These include: longitudinal vortex rolls, spatially periodic electric vortex flows, vortex shedding in a pool fire, and vortex instability over a non-isothermal horizontal flat plate. One study pertains to the fluctuations in particle–fluid flows. Two-equation turbulence models have been used to analyze turbulent natural convection.

Other studies

Natural convection in more complex geometrical configurations is considered in [66FF–72FF]. Free convection from power-law fluids is investigated for arbitrary geometries. An experimental and theoretical study of the convective drying of solids is made. A mathematical model is used to predict the spread of fire through fuel beds. Natural convection from wavy surfaces is experimentally investigated. Mixed convection in a Hele–Shaw cell is considered for a circular cylinder.

CONVECTION FROM ROTATING SURFACES

Rectangular channels

Heat transfer measurements have been made in rectangular channels rotating around an axis that is orthogonal to the channel axis [1G, 4G, 6G, 7G, 8G]. Theoretical studies have also been made on the thermal entrance region in laminar flow [5G], and in the fully developed regions in a rectangular channel [2G] and in a cylindrical channel [3G]. Experiments were performed for more realistic gas turbine engine conditions including serpentine passages [9G, 10G]

Rotating disks

Theoretical solutions for centrifugally-driven flow near rotating disks have been obtained with mass transfer at large values of Schmidt number [15G] and for power-law fluids near a disk with a step change in surface temperature [11G]. Solutions were presented for radial flow through a cavity consisting of parallel rotating disks and a shroud [12G, 14G] A similar study was made with no superimposed flow [13G].

Cylinders and annuli

Measurements have been made for heat transfer from a cylinder rotating about an orthogonal axis [16G], a rotating cylinder in cross flow [17G], and in an annulus with a rotating inner cylinder and a stationary slotted outer cylinder [19G]. A theoretical study was made of the heat transfer from a rotating cone with suction or injection in forced flow [18G].

Liquid films

Several papers reported work on the formation of liquid films on rotating disks used in processes such as spin coating [20G–24G]

Jets

Liquid crystal technology was used to measure the local heat transfer coefficient on a rotating disk with an impinging jet [26G]. Numerical solutions were obtained for the mixing of a lateral jet with swirling crossflow [25G].

Natural convection

Natural convection in a variety of rotating systems has been studied. Convection within a rotating, horizontal cylinder [29G], within a rotating spherical shell [30G], flow above an infinite rotating disk [27G] and flow in a rotating cubical tank with a heated bottom have been considered [28G].

Applications

Several applications of rotating flow systems were discussed [32G]. A theoretical analysis of a rotating annular reactor [31G] and rotating flow past a porous, heated plate [33G] were presented.

COMBINED HEAT AND MASS TRANSFER

Papers reviewed in this category cover a number of different areas. These include convective heat transfer to surfaces through which mass is injected into or taken out of the main stream, such as transpiration cooling, ablation, and film cooling. Also covered are jet impingement and wall jet heat transfer, and spray cooling where liquid drops impact on a surface. Drying systems are considered as are other systems with simultaneous mass and heat transfer.

Transpiration cooling

With transpiration cooling a surface is protected from a hot mainstream by having relatively cool fluid flow through the (permeable) surface. This cool fluid mixes and interacts with the hot mainstream. Transpiration cooling has been studied [1H–6H] in relation to hypersonic vehicles, asymmetric blowing, and flame tubes in combustion systems. Other geometries include channel flows with lateral injection, the thermal entrance region of an annulus and flow along a vertical plate and on a surface with either injection or suction.

Film cooling

Film cooling [7H–19H] has many applications in protecting surfaces exposed to high temperature gas streams. Particular emphasis over the last year has been focused on cooling of the fixed and rotating blades in the hot sections of high temperature gas turbines. Recent studies have described flow loss in a linear turbine cascade, film cooling on a flat surface, and the influence of acceleration, density ratio, and a second row of holes. Phenomena studied include the influence of swirl flow, vortices with different circulation, as well as pressure gradient and streamline curvature. Fluorescence measurements have been used to determine film cooling effectiveness and studies have been made on the discharge coefficient from film cooling holes to predict the pressure drop.

Jet impingement heat transfer — submerged jets

A number of studies consider heat transfer from submerged jets (e.g. air jet into still or moving air) impinging upon an opposite wall. Impinging jets can provide high local heat transfer in controlled regions where there is a high surface heat flux. Studies [20H, 22H, 24H, 27H, 28H, 33H, 34H] of circular jets indicate the effects of entrainment of ambient fluid on heat transfer with a single jet as well as an array of jets. The study of entropy production in impinging jets may be useful in getting further information on heat transfer. Supersonic impinging jets with crossflow and twisted jets have been studied. Comparison has been made between impinging isothermal jets and flame jets.

Impinging slot jets [21H, 22H, 25H, 26H, 29H–32H, 35H, 36H] are also widely used. Recent studies include the influence of impingement-surface curvature on heat transfer in the stagnation region on a flat plate and on a wedge surface. Other studies of stagnation region heat transfer include the influence of a moving surface. Models and experiments have been described for slot jets with flow through the surface on which they impinge, for annular jets, and for submerged jets of carbon dioxide in the region near its critical point.

Jet impingement heat transfer — liquid jets

If the fluid in a jet is very different in density from that of the ambient fluid through which it flows before impinging on a wall one has a free jet. Generally this might be a liquid (perhaps passing through air) jet. Heat transfer with liquid free jets can be quite large because of their high conductivity compared to the ambient gas. A number of studies with such systems have been performed recently [37H–44H], mostly experimental ones. A system was designed to organize overall measurements with slot jets with different thermal boundary conditions. Circular liquid jets have also been studied including single-phase jets in some case with collection of the spent fluid.

Spray cooling

Somewhere between submerged gas jets and free liquid jets is spray cooling in which a spray of liquid droplets impinges on a surface providing high local heat transfer [45H–48H]. Reports presented include experiments on water droplet sprays, interaction between droplets and surface mass transfer, analysis of the contact heat transfer in such impinging sprays, and the drying rates which occur in spray drying.

Drying

Heat and mass transfer are closely interlinked in drying systems. Studies recently done [49H–54H] include simultaneous estimation of heat and mass transfer coefficients, experiments on convective drying of materials, conduction effects in a desiccant/regenerator, drying of wet pipelines and paper, and fin surfaces for heat and mass transfer from moist air streams.

Miscellaneous

Other papers cover a variety of processes in which heat and mass transfer can occur simultaneously [55H–62H]. These include second law analysis of combined processes as well as examination of the entropy generated in heat and mass transfer systems. Numerical models have been applied to heat and mass transfer in ducts and experiments have been done on heat and mass transfer to partially wetted surfaces, Analysis and numerical studies have been done for falling film absorbers and crystal/melt systems.

CHANGE OF PHASE — BOILING

Thermal transport phenomena, associated with liquid-to-vapor phase change, continue to attract considerable attention in the heat transfer community. The 1991 archival literature reflects considerable activity in evaporation from droplets and films (48 papers), bubble characteristics and nucleate boiling incipience (22 papers), pool boiling (63 papers), flow boiling (43 papers), steam generators (15 papers) and two-phase thermohydraulic phenomena (17 papers). In addition to the 208 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 evaporation

The evaporation of small, single drops is of special importance in internal combustion engines and turbomachinery, as well as in various cooling and drying processes. During this review period, archival studies of the evaporation rate of a single isolated droplet included: development of a kinetic mass transfer model [15J], examination of the associated irreversibilities [11J], the use of a Lagrangian simulation to determine the influence of turbulence [6J], exploration of the effect of a nearby heated surface [48J], and of an electromagnetic field [5J]. While evaporation and heat transfer within a flowing gas/droplet mixture is the subject of refs. [14J, 20J, 23J], surface cooling induced by evaporating droplets is studied in refs. [1J, 44J], for single drops, and in refs. [28J, 27J] for humid air and mist flow, respectively. Refs. [24J, 41J] explore the effect of coatings on droplet evaporation from solid surfaces, ref. [38J] evaporation of droplets into an immiscible liquid, and ref. [40J] enhancement by electrostatic forces.

The successful design of refrigeration, distillation, desalination, and food processing equipment often requires an understanding of thin liquid film evaporation. Studies of surface evaporation from a cylindrical jet into a vacuum [35J], from a stationary liquid film into a gaseous flow [8J, 12J], from a thin layer of an aqueous solution [36J], from a film flowing in an inclined groove [42J], from turbulent falling films [3J, 21J], from corrugated surfaces [13J], from a surface exposed to arrays of circular air jets [43J], in the presence of a binary gas mixture [16J], and under the influence of a centrifugal field [9J] can all be found in the 1991 archival literature. The evaporative cooling of liquid films in smooth, vertical parallel-plate channels is explored in refs. [45J, 46J, 47J] and in smooth horizontal tubes and channels in refs. [19J, 31J, 39J]. The thermofluid characteristics of evaporative cooling in internally-finned channels are described in refs. [7J, 25J, 26J, 32J]. Solvent evaporation and diffusion within crystal growth apparati is discussed in refs. [33J, 34J].

The related phenomena of flashing, or explosive vaporization associated with homogenous nucleation in the bulk liquid is explored, for several different geometries, including drops [10J, 17J, 29J], jets [18J], layered liquid pairs [4J], and confined liquids [2J, 30J, 37J]. Existing applications and future possibilities for the use of homogeneous nucleation are discussed in ref. [22J].

Bubble characteristics and nucleate 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. Bubble formation at an orifice submerged in water and in a non-Newtonian liquid, as well as from a vertically-oriented nozzle in water, is examined in refs. [50J, 53J, 68J] respectively. The 1991 literature also addresses heterogeneous vapor bubble formation on a smooth surface [49J] and a surface covered with a porous coating, the departure diameter of bubbles [67J] in nucleate pool boiling [62J], and the liquid motion induced by nucleate boiling [59J]. Ref. [57J] describes the initial growth rate of a vapor-gas bubble, refs. [66J, 69J] bubble growth in a decreasing ambient pressure field, ref. [52J] an experimental study of gas diffusion from an air bubble into water, and ref. [56J] bubble break-up in a turbulent flow. The acoustic noise generated by a boiling liquid [54J, 60J, 61J] and the excitation [51J, 65J], as well as attenuation [58J], of thermoacoustic waves in gas–liquid mixtures are also described, along with the characteristics of gas bubbles in gas–liquid flows [70J] and in gas fluidized beds [55J], as well as in air–water fluidized beds [63J, 64J].

Pool boiling

Thermal transport by pool boiling from immersed surfaces continues to attract considerable attention. An overview of the boiling process, with emphasis on mechanistic models for all the boiling regimes, is provided in ref. [79J]. Ref. [123J] describes a new correlation of pool nucleate boiling based on nucleation site density; ref. [91J] provides detailed data on vapor bubble characteristics, and ref. [127J] proposes an expression for the nucleation site density.

Other studies in this category generally deal with particular parametric effects on pool boiling heat transfer, including the effects of heating methods [107J], the influence of subcooling [93J], and the impact of a centrifugal force field [100J]. The effect of the heater configuration on surface superheat and vapor bubble characteristics is examined in refs. [77J, 88J, 106J] for cylindrical geometries and in refs. [72J, 96J, 97J] for closed-bottom, vertical tubes and slots. While water is still the most common boiling liquid, cryogenic ebullient cooling of superconducting materials, with nitrogen [73J], helium [89J] and hydrogen [103J], and the results of boiling of hydrocarbon fuels [82J] are reported in the literature.

Effective industrial utilization of nucleate pool boiling requires accurate prediction of the peak nucleate boiling heat flux, or the so-called critical heat flux (CHF). Reflecting the growing challenge to the hydrodynamic instability models of CHF, ref. [105J] re-interprets the widely-used Kutateladze correlation in terms of macrolayer evaporation, ref. [90J] provides an improved macrolayer conduction model, and ref. [94J] suggests that a smooth, non-critical transition may be possible between nucleate and film boiling. The influence of heating surface thickness and size on CHF are explored in ref. [126J, 104J], respectively, and the effect of stepwise heating on CHF behavior is described in refs. [117J, 121J]. Interest in the critical heat flux associated with pool boiling of liquid nitrogen lead to the publication of refs. [74J, 101J, 102J].

At surface superheats in excess of those associated with CHF, nucleate boiling and film boiling appear to co-exist on the heated surface. Mechanistic studies of this "transition boiling" regime are described in refs. [95J, 120J, 131J], an analytical study of the temperature distribution across a heated surface in ref. [86J], and experimental results for the contact area of bubbles in ref. [129J]. Further increases in surface superheat lead to operation in the stable film boiling regime. The 1991 archival literature contains a relatively large number of film boiling studies, including development of a simple correlation for the minimum film boiling superheat [118J], large superheat film boiling from an upwardly-facing horizontal surface [80J], film boiling from a downwardly-facing flat plate [100J, 114J], and heat transfer in film boiling from a vertical surface [75J, 84J] as well as from an inclined plate [113J], from a rotating sphere [119J], from a horizontal cylinder [124J], and into a porous medium saturated with a binary mixture [81J]. The development of a thermal measurement technique for ceramics quenched in water is delineated in ref. [98J] and film boiling to helium in ref. [71J].

Analytical and experimental studies of the enhancement of pool boiling, especially in the nucleate boiling regime and at the critical heat flux, continues to occupy a large number of investigators. The effects of high-velocity, submerged liquid jets [108J, 111J], porous coatings [109J, 110J, 132J], porous structures [78J, 112J, 122J], miniature pin fins [115J], drilled plates in close proximity to the boiling surface [125J], and more conventional fins [85J, 83J] are described. The poorly-understood improvements associated with the boiling of liquid mixtures [87J, 92J, 128J], the addition of surfactants [76J], and the imposition of an electric field [116J, 130J] also received considerable attention.

Flow boiling

Heat transfer in flow boiling is intimately related to the mass fraction of the vapor and the prevailing flow regime and is, thus, strongly influenced by the enthalpy of the coolant and both the geometry and orientation of the coolant channel and/or the heated surface. The archival literature in 1991 documents several theoretical studies of the relationships among the commonly correlated flow boiling parameters [162J, 168J, 175J] and the generation and/or modification of flow boiling regime maps [155J, 167J]. Similarly, a careful search of the literature uncovers a phenomenological model for subcooled flow boiling [173J] and reveals several studies of flow nucleate boiling in vertical channels with low-velocity water [138J], isopropanol/water mixtures [172J], refrigerant R-113 [149J], and liquid nitrogen [136J], as well as ebullient heat transfer in a horizontal tube with a flow of refrigerant HFC-134 [148J]. Ref. [143J] discusses the onset of nucleate boiling in pipes, while ref. [153J] explores the boiling characteristics of a magnetic fluid flowing in a non-uniform magnetic field.

As in pool boiling, the critical heat flux represents the upper-bound on flow nucleate boiling and is a key design parameter. The recent literature has been enriched by new attempts to correlate CHF data [160J, 156J] and by experimental studies pertaining to high aspect ratio channels [139J, 152J, 169J], tubular nuclear fuel elements [147J, 157J], fuel rod assembly cells [137J], and arrays of thermally-simulated electronic components [164J], as well as with studies of CHF for nitrogen flow in a vertical channel [134J] and sodium sulfate in a vertical pipe [140J]. Two additional papers deal with the thermal behavior encountered during transition flow boiling of water [144J] and Refrigerant R-113 [165J] in circular tubes.

The heat transfer rates associated with post-CHF conditions in flow boiling are of particular importance in the design of nuclear reactors. An overview of recent work in post-CHF heat transfer is given in ref. [151J]. Several other articles discuss the performance of specific heated channel configurations, including a nuclear fuel rod bundle [170J], a spiral tube [158J], and a circular passage [150J]. Subcooled flow film boiling is examined in ref. [142J], for a wedge geometry, in refs. [133J, 146J], for horizontal flat plates, and in ref. [166J] for high velocity flow through a horizontal duct. Transient flow film boiling and the influence of thermal radiation on heat transfer in this regime, are explored in ref. [163J] and ref. [141J], respectively.

The cooling demands imposed by modern reactors, heat exchangers, and manufacturing processes have stimulated further effort in the correlation of flow boiling in augmented tubes and compact evaporators [154J] and the generation of enhanced flow boiling data for transverse and longitudinal ribbing [135J], twisted-tape swirled flow [161J], porous coatings [159J, 171J] and porous matrices or inserts [145J, 174J].

Steam generators

Much of the research in flow boiling is related to the design and optimization of steam generators. Consequently, some of the papers appearing in the 1991 archival literature deal specifically with various aspects of steam generator design, including the development of a mathematical model for heat transfer in a once through boiler [183J], the influence of porous coatings [189J] and surfactants [188J] on the thermal characteristics of steam generating equipment, and improvements in the sub-models used in the steam system simulators: RELAP/MOD2 [181J, 185J] and the Dynamic Simulator for Nuclear Power Plants [179J]. Due to the importance of helically-coiled tubes in steam generators, flow boiling behavior in this geometry and, in particular, nucleate boiling heat transfer [177J, 187J], helium-heating of the steam tubes [176J, 180J, 190J], heat transfer in the post-dryout zone [184J] and in the supercritical domain [186J], and the reliability of modular boilers relying on tightly-coiled tubes [178J], are singled out for detailed coverage in the archival literature.

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 vapor (void) fraction, two-phase flow patterns, and two-phase pressure drop encountered in liquid–vapor flow in tubes and channels. The literature provides discussion of the flow patterns which develop in small, horizontal rectangular channels [207J] and a horizontal flow divider [202J], the theoretical prediction of two-phase flow properties in coarse porous media [204J] and vertical separating flow [198J], as well as the thermohydraulic characteristics of mist-annular flows [205J] and film flow boiling [191J].

Modeling of thermohydraulic instabilities in two-phase flow is essential to the prediction of thermal transport rates and failure modes of steam generators. References [200J, 195J] provide broad reviews of void wave propagation and oscillatory instabilities, while refs. [193J, 201J, 203J] deal with instabilities encountered in vertical channels experiencing natural circulation and forced circulation, respectively. The application of fractal and chaos theory to flow boiling [199J], void fraction associated with non-uniform heating [194J, 197J], critical flow of boiling water in long pipes [196J], slug flow in horizontal pipes [206J], and boiling shock fronts [192J] are also described.

CHANGE OF PHASE — CONDENSATION

Research on condensation in 1991 included investigating the effects of tube surface geometry as well as system global geometry and thermal boundary conditions. There were modeling techniques presented and results of analyses and experiments with droplets, films, and jets were discussed. Several studies dealt with non-condensable gas effects, transient effects, the effects of having binary and ternary mixtures, and of having fluids with variable fluid properties.

Surface geometry effects

Numerous papers investigated the effects of fins, grooves and similar surface features designed for enhanced condensate removal. One showed the value of introducing a polyvinylidene coating to the surface and another investigated condensation on spheres filled with phase change material [1JJ–14JJ].

Global geometry and thermal boundary condition effects

Effects of geometry, including surface inclination, flow direction, and thermosyphon and vacuum column configurations were investigated. Additionally, the effects of electric fields, ion implantation, and rotation were discussed. Finally, effects of a variable wall temperature and variable fluid properties were documented [15JJ–30JJ].

Analysis techniques

Papers in this category stress analytical techniques. Topics range from application of a monomolecular condensate model to theories of recondensation and resublimation. Analyses were presented for short tubes and for non-Darcy flow within a porous medium. Methods were applied to the analysis of dropwise condensation, analysis of the effects of flow of departing condensate, and analysis of co-current channel flow. Models for simulation of power plant condensers were also suggested and a study of condensing flow in a steam turbine was reviewed [31JJ–43JJ].

Free surface condensation

Papers which investigate the growth of droplets in a vapor showed the effects of droplet diameter and velocity and flow within a horizontal tube. Other studies were on coexisting films and droplets, droplets in turbulent and separated flows, condensation at the stagnation point between two impinging flows, coaxial flows with condensation, and vapor condensation on a free surface mixed with a liquid jet flow [44JJ–51JJ].

Noncondensable gas effects

The two-phase boundary layer with non-condensable gas effects was investigated under forced convection. Recommendations on non-condensable gas effects for multi-stage evaporators and OTEC condensers were made [52JJ–54JJ].

Transient effects including nucleation

Film condensation of a rapidly-moving vapor and fog formation with simultaneous thermophoretic droplet deposition were investigated [55JJ–56JJ].

Binary mixtures and property effects

Studies with binary and ternary fluids include condensation on falling films, condensation of refrigeration fluid mixtures, and three-phase flash with partial condensation. Condensation studies were presented also for metal compounds, nitrogen, and fluids with variable condensate viscosity, Knudsen number or Stefan number. The effects of surfactants and organic heat transfer agents were also documented. One paper dealt with condensation of alkali halide crystals and another discussed the effect of dissociation [57JJ–71JJ].

CHANGE OF PHASE — FREEZING AND MELTING

Phase change problems, freezing and melting are reviewed in this section. Such phenomena take place in many processes of technological interest. Theoretical, experimental and numerical investigations have been attempted this past year. The various papers are subcategorized as follows: Stefan problems; solidification involving alloys/metals and casting processes; solidification: crystals and directional solidification issues; freezing and melting: frost, ice and snow; freezing/melting and thawing: applications; convection effects; continuous casting processes and mold filling; methods, models and numerical studies; special experimental/analytic and/or comparative studies; thermal storage; and miscellaneous applications.

Stefan problems

An enthalpy formulation for the Stefan problem is discussed in [1JM].

Solidification of alloys/metals and casting processes

Papers in this subcategory involved theoretical, numerical and experimental investigations which deal with various aspects of phase change in alloys and metals and casting processes. Studies in this subcategory included knowledge-based systems involving CAD for casting processes, continuous casting studies, freezing and solidification of binary alloys, solidification simulations in centrifugal casting processes, and studies involving solidification behavior and material deformation in strip casting process [2JM–11JM].

Solidification: Crystal and directional solidification

There has been a lot of research activity this past year on a variety of issues relating to crystal growth and directional solidification. The numerous investigations include issues relating to crystal growth simulations, directional solidification, instability, convection effects, magnetic gravity, and thermal field influences, and thermal stresses induced during solidification of crystals. These papers involve theoretical, experimental and numerical computer simulations [12JM–83JM].

Freezing and melting: frost, ice, snow

Papers in this subcategory include calculations of thermal resistance of cryoscopic deposits, measurements of growth in ice, melting of ice in a porous medium, holographic interferometric measurements, frost growth in a forced air stream, and melting heat transfer in fluidized liquid–ice beds [84JM–90JM].

Freezing/melting and thawing: Applications

Research in this subcategory involved cyclic melting and freezing, microwave thawing of cylinders, effects of porous layers and pulsed concentration of energy fluxes, mathematical models of thawing, rapid solidification issues, direct contact melting processes, buoyancy and surface tension effects on metal melting, gravity and solidification-shrinkage in ingots, and fibre formation during melt extraction [91JM–100JM].

Convection Effects

Theoretical, experimental and numerical papers appear in this subcategory addressing effects due to convection during solidification. Issues included surface-velocity induced convection, steady solidification of a liquid on a moving wall with forced convection, natural convection effects, cross-flow effects, gravity conditions, convective stirring, solutal convection and viscous–inviscid interactions [101JM–112JM].

Continuous casting and mold filling processes

A numerical study involving finite element modeling of turbulent fluid flow and heat transfer in a continuous casting appears in [113JM].

Methods, models, and numerical studies

Numerous papers which appear in this subcategory address new methods or modeling techniques and studies involving numerical simulations. The studies involved thermal diffusivity differences across interfaces, crystal growth studies, melting and freezing, non-linear processes, flow-thermal effects, alloy solidification, solidification in pure metals and directional solidification [114JM–124JM].

Special experimental/analytical and/or comparative studies

Those papers which have conducted special experimental studies, analytical and/or drawn comparisons between experiments and simulations appear in [125JM–128JM].

Thermal storage

Papers addressing problems related to thermal storage appear in [129JM–132JM].

Miscellaneous applications

A variety of miscellaneous applications dealing with freezing and melting have been studied. The reader is encouraged to refer to them in [133JM–174JM].

RADIATIVE TRANSFER PROCESSES

Radiative transfer is important in a variety of high temperature systems, but until recently, many problems have been difficult to analyze because of the difficulty in solving the integro-differential equations involved. Numerical techniques have been developed rapidly over the last several years, and a number of researchers are now employing spherical harmonic approximation (first order = P_1 and third order = P_3 are popular) and discrete ordinate (fourth order = S_4) methods to solve the radiative transport equation. This solution is often coupled with finite element solutions of the energy equation, and sometimes continuity and momentum equations as well. The following subsections review the past year's research in several application areas.

Multidimensional models and enclosures

As mentioned above, numerical solutions have advanced rapidly in the last several years, and papers [3K–5K, 9K, 10K, 14K, 15K, 17K, 19K, 23K, 24K, 26K, 27K] present a variety of techniques applicable to rectangular enclosures with both participating and non-participating media. Examples include zonal methods, discrete ordinates, finite element, boundary element, Markov chains, an n-bounce approximation, and even an analytical method. Implementation of a Monte Carlo technique on a massively parallel computer was also discussed [11K], as were concentric spherical cavities [2K, 12K]. Two papers examined the applicability of mean surface temperatures for heat transfer in rooms [13K, 6K], while one other presented work related to the optimal placement of radiators [16K].

Related to the above works were some developments in calculating view factors for various geometries [1K, 8K, 22K, 25K], as well as an algorithm for calculating the mean projected areas of seated and standing people [21K]. In addition, other theoretical treatments of multi-dimensional radiative transfer in non-enclosed systems with participating media [7K, 18K, 20, 28K] were published.

See also the following papers in subsequent subsections: [63K, 77K, 97K, 102K, 113K, 116K].

Radiative transfer in scattering media

Five papers presented theoretical calculations of transmission, absorption, and/or scattering in aerosol/particulate media [31K, 33K, 34K, 56K, 58K], including polarization and multiple scattering effects, cylindrical geometries, and applications to solar thrusters and spray coating systems. Experimental measurements, generally used in conjunction with inverse scattering models, were presented in [29K, 53K, 59K]. Other studies examined different geometries or media properties such as anisotropy or inhomogeneity [32K, 35K, 36K, 37K, 39K, 48K]. Interactions between particles and incident fields were also reported, e.g. chain agglomerates and coated spheres over a substrate, as well as the internal distribution of absorbed energy within spheres [40K, 50K, 51K, 57K].

Radiative transfer through packed beds [38K, 41K, 42K, 43K, 52K] and porous media [45K, 47K, 49K] also received considerable attention, with a new gas–gas heat exchanger based on the latter. Theoretical and experimental results for fiber systems are presented in [44K, 46K, 55K], while [30K] estimates the error incurred by employing diffusive transfer models near boundaries in such media.

Related papers in other subsections include [7K, 9K, 19K, 76K, 78K, 87K, 89K, 90K, 92K, 98K, 110K and 135K].

Radiative transfer in gases

Several papers presented theoretical models, including a new method dubbed the harmonical transmission model, which is reportedly capable of accounting for spectral line structure in multi-dimensional radiative transfer calculations [63K]. Other models included a discrete ordinates solution method for non-gray gases [62K] and a model for gas–surface interactions under the condition of a temperature discontinuity [65K]. Emission and/or absorption by H_2O, CO_2, and mixtures thereof are discussed in [67K, 69K, 72K]. The influence of gas flow velocities and velocity gradients in plasmas are described in [60K, 66K, 70K], while non-equilibrium and equilibrium radiative transfer behind reentry shock fronts were simulated in [61K, 64K, 68K, 71K].

Related papers in other subsections include [9K, 27K, 59K, 86K, 128K, 133K].

Radiative transfer in combustion processes and systems

Since radiation from hot gases and particulates are often important in combustion systems, a number of papers examined the effect of radiant heat transfer on flame characteristics. Examples include premixed gases in a vertical tube [74K], candle flames [84K], luminous and non-luminous turbulent diffusion flames [79K, 82K], droplet burning [85K], particle suspensions [76K, 90K], and porous burners [78K, 87K]. Radiation was also found to play a significant role in oil pool and wood structure fires [80K, 81K, 88K]. Rounding out this category, both numerical modeling and experimental measurements of combustion systems ranging from rocket engines [77K] to fluidized be combustors [89K] to boilers and furnaces [73K, 75K, 83K] to exhaust flues [86K] were reported.

See also [101K, 105K, 106K] in other subsections.

Radiation combined with conduction

Several numerical methods were investigated for their ability to accurately solve two-dimensional or transient combined radiation/conduction problems in participating media [92K, 96K–99K]. The introduction to [97K] may be particularly useful to those unfamiliar with alternative numerical techniques, and the body compares the results of several methods. Two related papers considering the behavior of plane layers of liquid organic compounds [91K, 100K] were also published. Finally, papers [93K–95K] consider radiative transfer from fins, with the aim of optimizing fin geometry and/or mass.

See also [119K, 124K] in other subsections.

Radiation combined with convection

Five papers presented numerical solution methods for combined radiation and convection in enclosures [102K, 103K, 108K, 113K, 115K], with two papers looking specifically at flow in pipes [104K, 116K]. External flows included studies of fins and plates [110K, 111K, 114K], and plane layers [112K]. As one might expect, the radiation component was dependent on the characteristics of the media involved, and played an important role in determining temperature, heat flux, and velocity profiles.

A series of papers considered specific systems in which coupled convection and radiation was considered. Among these were numerical simulations of turbine vanes [105K, 106K], chemical vapor deposition chambers [101K], circular foil heat flux gauges [107K], and thermal imaging of terrestrial objects [109K].

Papers [26K, 58K, 70K, 73K] may include additional information of interest.

Surface interactions/laser irradiation

The papers in this section focus on the response of various surfaces when subjected to an incident radiation flux. Applications of laser welding and cutting are covered in the section on Conduction, so the papers listed here concentrate on laser ablation of metal foils, which is used in X-ray lasers and fusion experiments [120K, 121K]. Several other papers discuss substrate heating processes which may or may not incorporate lasers [117K, 123K], while others model interactions with diffuse or incoherent radiation fluxes [118K, 124K]. Absorption characteristics for short wavelength radiation are also important for shielding applications involving X-rays and gamma rays [119K, 122K, 125K]. Obviously, many more papers in these fields have appeared elsewhere, but these papers considered the associated heat transfer phenomena in some detail.

See also papers [131K, 134K, 139K] in the next section.

Radiative properties

Properties of interest in radiation calculations include emissivity, absorptivity, transmissivity, and reflectivity, which apply to gaseous as well as condensed phase systems. The wavelength dependence of these properties is often of primary importance in modeling radiative transport. In systems comprised of more than one material or phase, scattering is also important, and the directional properties of the scattered field need to be estimated. These depend on size, morphology, and refractive index of the scattering particle/surface, as well as on characteristics of the incident radiation.

Experimental measurements and analytical predictions of the radiative properties of various metallic, oxide, semiconductor, and superconductor thin films were reported [127K, 130K, 132K, 136K, 137K]. Application-specific material properties encountered in cryogenic systems [126K], laser cutting of Cu and Al [139K], radiation shielding [131K, 134K], and carbon reinforced plastics [129K] were also presented. A molecular model for predicting the far infrared spectra of arbitrary gases and liquids was discussed in [128K], and the spectral distribution of CO emission/absorption was modeled in [133K]. Finally, the refractive indices of alumina particles [135K] and fibers [138K] were measured.

Additional papers of interest include [46K, 47K, 51K].

Experimental methods and devices

This section includes papers describing new radiation sources for such applications as extreme ultraviolet generation, miniature sources, and high power gas discharge lamps capable of MW m^{-2} heat fluxes [141K, 143K, 144K, 145K]. Also included are descriptions of a high speed near infrared spectrophotometer [146K] and a direction selective radiometer designed specifically for pyrometric measurements of molten metals in vacuum chambers [142K]. In addition, a review paper describing uses for and measurements of the optical Kerr effect [147K] and a book review of a monograph on radiation thermometry [140K] may be of interest.

Readers should also check the section on Experimental Techniques and Instrumentation, as well as the following papers cited under other categories here: [46K, 47K, 91K, 93K, 94K and 107K].

NUMERICAL METHODS

The number of publications pertaining to numerical methods is increasing very rapidly. New numerical methods are developed vigorously and applied to a wide variety of problems. In this review, the papers that focus on the application of a numerical method to a specific problem are included in the category appropriate to that application. The papers that deal with the details of numerical method are reviewed in this section.

General review articles

A number of review articles [1N–12N] pertaining to numerical methods have appeared. Some of these papers describe the use of computational fluid dynamics in different industries (including petrochemical industry). General issues regarding the solution of the Navier–Stokes equations are discussed. Computer software for the solution of flow and heat transfer is described. One paper deals with the simulation of fire in an aircraft, while another presents the concept of cellular automata for analysis.

Heat conduction

Heat conduction continues to be an important area of interest as it provides a testing ground for a number of numerical methods. Research continues on techniques employing finite-difference, finite-element, and boundary-integral methods. The papers on heat conduction [13N–31N] deal with irregular geometry, moving boundaries, and non-linearity. In addition to the conventional methods, a combination of the Laplace transform and the finite-element method has been proposed. Some articles have employed methods for conduction and radiation. Fluid/thermal/structural interactions have also been considered. Methods dealing with mass diffusion employ a methodology similar to that for heat conduction.

Convection and diffusion

The formulation of a satisfactory numerical method for the treatment of the convection and diffusion terms in the transport equations for momentum and energy continues to be a topic of major interest. New schemes are proposed to reduce the numerical diffusion that is present in lower-order schemes. It is also important that the scheme does not lead to unphysical wiggles in the solution. The papers in this category [32N–53N] examine false diffusion in lower-order upwind schemes and present new schemes that produce less diffusion and remain bounded or wiggle-free. Some of the suggested schemes are third-order upwind scheme, upstream-weighted higher-order scheme, and other variants.

Phase change

The special features involved in the calculation of heat conduction with phase change have been described in [54N–72N]. The use of the enthalpy-based method is quite common. Some techniques employ a fixed grid, while the use of adaptive remeshing is proposed in others. Inverse techniques for phase change have also been described.

Fluid flow

Since the calculation of convective heat transfer is so important, the solution of the flow field becomes an essential ingredient of the total heat transfer solution. Considerable amount of work has been reported on methods for solving the flow equations [73N–117N]. These include the finite-difference and finite-element methods. Some emphasize the solution of the natural convection problems. Methods employing staggered and non-staggered grids have been proposed and compared. Adaptive grids and adaptive finite elements have been employed. To improve the efficiency of solution, multigrid methods and direct solvers have been proposed. In addition to the standard methods, the use of Monte Carlo techniques, of spectral methods, and of vorticity-potential methods is described.

Other Studies

A number of other studies [118N–129N] related to the numerical solution of fluid flow have been reported. These include the use of turbulence models, large-eddy simulation, and direct numerical simulation of turbulence.

TRANSPORT PROPERTIES

As in previous years the research in this area occurs most extensively in the subcategory of thermal conductivity, its measurement and estimation for a variety of substances and mixtures. Noteworthy is the attention directed toward composite materials.

Thermal conductivity

A number of general studies examined the temperature dependence of thermal conductivity of metals and semiconductors in solid and liquid phase, the conductivity of dense fluids and their mixtures, the effective conductivity of three-phase systems, and the use of a converged laser beam to determine thermal diffusivity of microscale samples.

For specific substances results have been reported for liquid nitrogen (transient hot wire method), uranium hexaflouride (by reactor heating), gaseous helium-3, ten amorphous alloys, a-mercuric iodide, several glasses, alternative substances to CFC compounds, selected superconducting materials, pressure-sintered alloys, five rock-marble samples and the powdered cryogenic insulation perlite.

For composite materials several aspects are considered: conductivity measurements of high temperature superconductor composites, influence of interfacial layer at low temperature, conductivity of filled epoxy composites and sintered metal fibers, effective conductivities of ceramic-fiber insulations, fiber-reinforces composites, and Knudsen diffusivities in structures of randomly overlapping fibers. The calculation of thermal conductivity of heterogeneous composites is considered as is the related problem of heat conduction through multi-layered media.

The conductivity of films and coatings receives attention as does micro electronic encapsulants. At low temperatures a number of studies treat: conductivity of magnetic intermetallic compounds, contact conductivity of insulation material, liquid crystal polymers and modified epoxy resins. The influence of internal cavities on overall thermal conductivity is reported on in several contexts, e.g. foam plastics and dried powders [1P–52P].

Diffusion

Measurements are reported for the diffusion coefficient in heteropoly acid catalyst, the effective coefficients for commercial catalysts and for nitrogen monoxide through porous ceramic catalysts. An estimation method is given for coefficients in multicomponent liquid systems [53P–56P].

Specific heat

Several papers report measurements at low temperatures: an epoxy resin below 1 K, zerodur and zerodur M, gadolinium near the Curie point, and the use of carbon and thick film chip resistors as thermometers in heat capacity determination [57P–60P].

Thermodynamic properties

The estimate of various thermodynamic properties includes an equation for calculating the vapor pressure of organic solids and vapors, oil and gas condensate mixtures and the use of mixture fusion properties to interrelate excess thermodynamic functions. Multi-component mixture heat and mass transport is considered from the viewpoint of irreversible thermodynamics and simple metastable liquids examined by theories of the liquid state. Real air acoustic velocity and isentropic exponents are reported [61P–67P].

Transport properties—combined

A collection of expressions are reported which readily yield thermophysical property values for saturated fluid and compressed liquids of technical interest; a method is suggested for calculating the Prandtl number; and averaged transport equations for multiphase system with interfacial effects developed. For reacting systems the effect of uncertainty in the constants in gas phase air reactions is assessed, turbulent diffusivities are considered, energy quantities reported for the formation, vaporization and sublimation of organics. For particulate systems heat transfer is considered in dense media, suspensions of inelastic particles, and moderate concentrations of suspended rigid spheres [68P–76P].

Viscosity

The viscosities of liquid mixtures are modeled and a generalized viscosity equation for pure, heavy, hydrocarbons developed. The viscosity of several glasses is measured and the corresponding states principle tested for atomic transport properties. The viscosity in hysteretic systems is approached stochastically [77P–81P].

APPLICATIONS

An impressive number of works, analytical and experimental, explore various aspects of heat exchangers applied in widely diverse technologies.

Heat pipes

Analytical models predict the overall thermal performance for a gas–gas exchanger, guide the design of high performance sintered-wick devices and address the problem of film condensation within a finned, coaxial, rotating heat pipe. Transient considerations dominate a number of works: vapor dynamics during start-up, characteristics of a micro device, one-dimensional compressible flow, non-conventional pipes with uniform and non-uniform heat distributions and a method for reducing solution computer time. Other works examine heat transfer control by magnetic fields, thermal coupling in double-pipe exchangers and entrainment limitations.

Experimental efforts study gravity and non-condensable gas effects on condensation and heat transfer rates in a closed, two-phase device operating in fully-developed boiling regime. As was the case with the analytical works, transient operation is also the focus of measurements: start-up of a frozen heat pipe, behavior of micro-heat pipes in ceramic chip thermal control, high and low temperature units with multiple heat sources and sinks, short, low-temperature pipes, and the use of heat pipes in developing geothermal energy. Liquid flow in pipe wicks and the permeability of screen wicks also receive study [1Q–24Q].

Heat exchangers

The review of the large body of information in this subcategory was facilitated by further subdivision.

Design. Numerical models, algorithms, empirical relations are directed toward perfecting and simplifying the design process. A few experimental studies further our basic knowledge. A second law approach to design is presented by some authors; others advocate improved measures of thermal efficiency. Crossflow exchangers for optimal surface area and maximum effectiveness are described. Consideration is given to specific exchanger types or factors influencing their design: flow configurations, the microtube strip version, variable heat capacity and high-N_{tu} exchangers, predicting critical heat flux in rod bundles, turbulent flow in furnace chambers, axial flow effects in condensers and models for exchanger control in nuclear power plants. Survey results provide a glimpse of heat transfer in the 21st century [25Q–44Q].

Direct contact and evaporators. Analytical models are proposed for spray-column exchangers and evaporators and measurements given for air bubbling through water, and the performance of a nocturnal radiator. Cooling towers are studied parametrically and in counter and crossflow. An inflated fabric cooling dome is evaluated as an alternative to conventional designs, and intensive heat transfer surfaces advocated for refrigerators [45Q–52Q].

Enhancement and extended surfaces. The electrohydrodynamic (EHD) technique for enhancing heat transfer is pursued by a number of investigations who report impressive results. For tubular exchangers a comprehensive study of heat transfer enhancement is reported and an optical design for closed finned channels described. Heat flow and pressure drop data for finned tube banks is the focus for a number of works including one which deals with the effect of radial ridges on the fin surfaces. The influence of fin and pin-fin profile shapes is studied as well as the effect of sidewall ejection flow, and individually finned, flat, multichannel tubes, tubes with spirals, tubes with corrugations, and helical tubes are investigated experimentally for their influence on heat transfer. Grooved surfaces of a vertical tube are studied as a means of achieving nucleate boiling stability in the liquid film. Internally fined tubes, wavy and corrugated fins and louvered fins are all examined for their enhancement potential though caution is given that extending surfaces does not always result in improvement in heat transfer. Other works consider the influence of segmented surfaces, passages with sharp turns and swirl generators [53Q–82Q].

Fouling, deposits and surface effects. Fouling, depositions and surface effects influence the effectiveness of heat exchangers. Accordingly, a number of efforts seek to analyze the change in thermal efficiency when a uniform fouling deposit is added to an extended surface, to determine the influence of scaling on the performance of shell-and-tube units, and to study microscopically the effect of $CaCO_3$ scaling on exchanger surfaces. Additional factors are considered: effect of variable surface roughness, particle motion and deposition in channels and around a cylindrical surface, influence of oil on energy flow in refrigerant evaporators, and an investigation of a method which simultaneously measures the fouling factor and water velocity in a tube. The use of titanium to counter sea water corrosion, wear damage of tubes due to flow induced vibrations, and the comparative performance of two fouling probes conclude the work in this area [83Q–93Q].

Materials. High performance titanium provides tubes able to withstand highly corrosive conditions. Surface treatment of Al–brass products with trianzinethiols is found to promote dropwise condensation and a PVC exchanger is field-tested for use in housing animals. At very low temperatures new silver powders with large surface area have become available as an exchanger material, porous coatings are tested for heat exchanger material, porous coatings are tested for heat exchanger with superfluid helium and a survey report the status of knowledge for frequently used soldered aluminum plate exchangers [94Q–98Q].

Networks. For heat exchanger networks a new design option is discussed, a sensitivity analysis is presented, and a new concept, the diverse pinch, described for heat exchange network synthesis. For the later the use of a dual temperature approach is noted.

For district heating networks a code is being developed for dynamic calculations and the disadvantages of steam use in such instances is reviewed [99Q–104Q].

Packed beds. Fluidized beds are investigated using an emulsion layer model for wall heat transfer and liquid–solid beds modeled using an immersed heater. Energy storage using the two-phase model is simulated, the thermal characteristics of packed bed storage modeled, and a metal hydride heat transformer tested. The matrix exchanger is analyzed as is the influence of temperature and moisture on energy storage in loose granular systems [105Q–111Q].

Regenerators and rotary devices. A solution is proposed to the regenerator problem involving asymmetric-unbalanced counterflow using Galerkin's method. In another work an optimization of the regenerator is sought with respect to volume and energy efficiency. For rotary heat exchangers interest focuses on desiccant cooling systems and the effect of air purging on efficiency of energy recovery [112Q–115Q].

Shell and tube exchangers. Physical modeling is employed to search for possible vibration tendencies of the mechanical elements of heat exchangers. For laminar flow in porous tubes the finite element method is used to describe the flow field. The same technique is applied to exchangers with phase change. A new dynamic model is tested against measured exchanger behavior and the transient responses of an exchanger are predicted using feedback control loop analysis. Aspects of tubular exchangers have been combined with those of plate-type exchangers to create a hybrid which has improved heat transfer [116Q–121Q].

Transient. Several works treat exchanger behavior under transient conditions: the response of gas-to-gas cross flow exchangers with primary fluid inlet temperature variation and in a second instance with regard to finite wall capacitance. Another paper presents an analytical method for analyzing non-stationary processes in exchangers and the response of pulsed gas laser exchangers to periodic temperature inputs is considered. An exchanger cooled by natural air convection is modeled and compared with experimental results, tube oscillation in two-phase heat transfer is analyzed, and approximate solutions found for the transient response of a shell-and-tube exchanger [112Q–129Q].

Miscellaneous

A number or works cover applications not included above but important in certain technical areas: enhancement of refrigerant vapor absorption, aspects of automobile heat exchanger operation, thermal loading for concrete roof slabs and walls, drying, and cooling of electrical and electronic components. Other efforts treat the cyclone exchanger, exchanger defrosting and the performance of an exchanger-type anaerobic biofilm reactor. Fire research results are reported by a group of papers and the thermal performance and analysis of split-flow exchangers discussed.

Heat pump exchangers and heat pump use to assist distillation systems are investigated, the problem of exchanger leak detection taken up, and the influence of mixing in stirred apparatuses considered. At low temperatures the thermal efficiency of short heat exchangers is measured and the cooling of commercial thermal analysis systems discussed. Further efforts deal with applications in a number of areas: nuclear containment cooling systems, steam generators, heating plants, heat engines, fuel-cells, refrigeration, heat-recovery systems, heat storage, rail transportation, waste disposal, waste water treatment, and pre-heating of winter ventilation air in livestock enclosures [130Q–167Q].

HEAT TRANSFER APPLICATIONS — GENERAL

Aerospace

It is shown that the ram jet combustion wall of a hypersonic plane can be cooled with hydrogen gas [102S]. The transient behavior of an active thermal protection system for rocket nozzles and reentry vehicles was studied [63S]. The design and redesign of the Galileo spacecraft is described [81S, 98S, 99S].

Bioengineering

A hypothermia protocal can be designed based on a finite element model of a tumor bearing human lower leg [26S]. The transient temperature field created in skin during surface burn is studied using a finite element technique [30S] showing that *in situ* burns can be modeled by experiments using a flap chamber.

Digital data processing, electronics

A data bank is being set up in France at the Centre National d'Etudes des Telecommunications to study the principles for selection of thermal modeling codes and the choice of package values [56S]. Experiments studied boiling heat transfer from a 12.7 x 12.7 mm heat source to a jet of Fluorinert FC-72 [69S]. Experiments investigated also the heat transfer from model packages with fins in a channel between circuit boards for a variety of heat sinks [66S]. The effectiveness of different heat transfer paths on the overall thermal performance of a typical electronic package was investigated in a numerical study [91S]. It is concluded that natural convection has only a minor effect. The effects of thermal fluid interactions of neighboring components on air-cooled circuit boards are reviewed [62S].

Energy

The coolant and cylinder wall temperatures of *diesel engines* during the warm-up period are estimated [108S] and wall heat losses are studied by similarity considerations [33S]. Conservation laws of near wall turbulence are used to calculate convective heat transfer [49S].

Secondary flows near the end walls of *gas turbines* are studied by visualization and local mass (heat) transfer measurements [46S]. Infrared thermography is used to obtain local heat transfer coefficients in turbine blade passages [59S]. Attention is directed toward partial load conditions of stationary gas turbines [89S].

Computer models predict convective heat transfer and boiling transition in *nuclear reactors* using boiling water [2S, 43S]. Transient heat transfer during loss of coolant is discussed [35S] and studied experimentally [50S]. Energy storage is discussed [83S].

Experiments on flow and heat transfer in a *chemical reactor* result in good agreement with a finite modeling analysis [34S]. Expressions for heat transfer in a draft tube are derived [106S].

Models are developed for the study of heat transfer in reheating *furnaces* and blast furnaces [25S, 18S]. Complex heat and mass transfer causes erosion of refractories [1S].

Heat transfer is studied in a lithium bromide *refrigerator* [14S], for a cool storage system [82S], for helium superconducting magnets [84S], and for HFC-134a and CFC-12 [32S]. Equations for heat and mass transfer are derived for adsorption cooling/heating systems [42S]. Potentialities of active insulation for cryogenic machines are studied [94S] and numerical analyses of heat transfer in a cryopump were performed [58S].

Experimental and analytical studies deal with heat pipes [5S] and thermosyphons [27S, 36S], with removal of contaminants on heat transfer surfaces [57S], heat transfer and fluid flow in discharge lamps [24S]. An analysis looks at cold storage in porous capsules [28S].

Environment

Several papers consider heat transfer in *buildings*, specifically through a slab on ground [4S, 41S], frosting effects [103S], sensitivity to workmanship [105S], the thermal response of a roof to intermittent spraying [3S], the indoor radiant environment studied by Monte Carlo simulation [73S], and energy conservation by preheating of air in earth tubes [72S].

The heat extraction from a hot dry rock geothermal reservoir in the *ground* is modeled [71S] as well as for aquifers [19S, 90S]. Energy budget models for lakes under various atmospheric conditions were compared with experimental results [96S].

The temperature field in the nocturnal stable boundary layer of the *atmosphere* resulted from a solution of the energy equation [101S]. Global warming can be detected by the spatial temperature variation in the earth [114S]. Field measurements determined heat transfer in an urban canyon [117S].

The characteristics of *fires* were studied on an aircraft cabin [53S] and in forests [38S, 39S, 47S].

Manufacturing, materials processing

The thermal aspects of processing methods are studied by numerical simulation, in a few cases compared with measurements for drawing [67S, 115S, 48S], rolling [78S, 86S, 115S], grinding [55S], welding [80S], cutting[21S], laser cutting [13S], and annealing [118S]. Heating of titanium particles by laser radiation is investigated [10S].

Conjugate heat and mass transfer in convective *drying* is discussed [31S]. Processes considered are: intermittent core drying [121S], vacuum drying of viscous food [52S], atmospheric drying of peat [112S], superheated steam drying of glass spheres [87S]. The state of drying in the French industry [54S] and future technologies [70S] are examined.

Thermal aspects of *melting* occur in continuous casting [20S], in spinning of nylon [74S], in melt spinning [37S], in molten slags [68S], in gas injected iron baths [109S], in the ball forming process of semiconductor chips [44S] and in freeze-drying of thin plates by microwaves [93S].

Heat transfer in agitated vessels [97S] and in mixers [12S], between a water cooled belt and a metal [95S] are examined. Computer-aided engineering enters the foundry industry [92S].

Analyses are performed on *deposition* processes [60S], on calcium carbonate deposition [22S, 23S], on epitaxial deposition of silicon [61S], of spray-deposited tin–lead alloys [16S], on coatings of refractory metals [110S].

Fluid motion due to a stretching surface occur in extrusion processes [111S]. Injection molding is studied by analysis and measurements [64S, 65S] also for rubber [45S]. Microwave heating of food and polymers [11S] and retort heating of liquid food [51S] found attention.

Temperature maps showing the surface temperature caused by frictional heating of a couple of dry sliding solids [9S] are useful in tribology.

SOLAR ENERGY

A high level of interest and activity characterizes the research in this sector.

Buildings and enclosed spaces

A number of papers pertain to maintaining comfortable conditions in enclosures exposed to high ambient temperatures. These include a large research center building cooled by solar energy, the design and thermal analysis of passive solar houses, natural-cooling techniques for residential buildings, cost-effective use of thermal insulation, and the reduction of heat loads on tents caused by solar radiation during extremely hot weather.

Other works investigate the effect of solar absorptivity and emissivity of exterior surfaces on the thermal performance of buildings and wall design for heating and cooling in North African climates. Multi-layer walls and their thermal response factors and the influence of additional thermal insulation (prefabricated, lightweight panels) on the performance of existing walls are also investigated. Glazing and its influence on building energy behavior is the focus of a number of works including the use of coated, low-emissivity glass, tinted and reflecting glass and multiple layers of glazing and various mounting and seals.

The direct solar slab heating floor is modeled, the heat loss to ground from a buildings studied, and an isothermal mass is employed to stabilize the temperature of a "winter house" in a cold region in India. Solar energy storage for a dwelling and the thermal behavior of sunspaces are simulated, and the effective heat storage capability of a building estimated [1T–20T].

Collectors

A number of studies are of general interest. The thermal behavior of a solar collector is modeled numerically and account taken of the effect of non-uniform and non-steady boundary conditions. The maximum efficiency for collectors, with and without concentration and utilizing diffuse solar radiation, is investigated.

For concentrating collectors the following features are considered: a two-stage optical, parabolic trough equipped with tubular absorber design, two stage fresnel reflector analysis, flux density distribution in the focal region of an optical system and analysis and design of two stretched-membrane parabolic dish types. Other papers treat radiant energy transmittance for honeycomb and parallel slat arrays and heat exchange in a multi-cavity volumetric receiver. The influence of geometry is considered by work considering the influence of pipe radius on energy gain, optical properties of v-trough receivers and the performance of a cylindrical collector.

For flat-plate designs the effect of cover thickness and double glazing on top loss is reported, as are test results for a tubeless phase-change collector and the use of dielectric materials in condensers for energy collection. Application of solar collectors for assisting a heat pump and preheating ventilation air for farm buildings join the growing list of uses for this energy source [21T–40T].

Radiation characteristics and related effects

The design and optimization of solar energy devices require accurate data of hourly global and diffuse radiation which in turn depend on local conditions. In addition, quantities such as ultraviolet radiation, relation of diffuse to global radiation, global radiation to sunshine duration, comparison of estimated and measured hourly and daily solar fluxes, spectral band energy distribution, seasonal correlations and others are reported for the following locations: Arctic and alpine sites, various Australian stations, Bahrain and Dhahizan in Saudi Arabia, Rio De Janeiro, Lesotho in Southern Africa, a French Mediterranean site, eastern Nigeria, Sri Lanka, and Turkey. Such factors as atmosphere haze, short-wave sky radiance in an urban atmosphere and for cloud cover conditions are also treated. The response of Arctic permafrost to global warming is considered in a related study. The effect of tilted surfaces on received radiation and the modeling of this process is the focus of a number of investigations. [41T–62T].

Solar heaters, cookers and dryers

These devices often are the end application of solar energy and occur with increasing diversity. There are combined concentrating/oven type cookers, mirror boosters for solar cookers, finned matrix and packed-bed air heaters and performance prediction of a corrugated cover heater. A useful review of testing procedures for air heaters covers various experimental techniques and describes a method for generating design data. For domestic water heaters the problems encountered by those operating on thermosyphon flow are discussed and a two-phase thermosyphon heating system simulated by a computer model; a partially insulated heater with natural circulation is experimentally studied; the economics of energy conservation and payback periods examined for large water heaters and a rating method for domestic hot water systems presented.

Solar pools and ponds are the focus of several papers: design parameters for indoor swimming pools, lake evaporation, performance of a pond heater with semitransparent, multilayer surface insulation and a survey of work on salt gradient solar ponds. Related heating processes involve melting wax, photocatalytic destruction of chlorinated solvents, solar dryers for copra production and the effect of reflectors to boost dryer performance [63T–83T].

Stills

Several factors influencing the performance of solar stills are examined: radiation transmission across a salinity gradient, density plumes in salt gradient ponds, internal air motion, and water depth. Analytical works consider: thermal efficiency for a passive still, performance of a high temperature system, and heat-transfer coefficient estimation. Greenhouse heating and solar still combinations are also studied [84T–93T].

Power and reversed cycle systems

The use of solar energy for lunar power, process heating and storage is the major theme of a number of papers treating several aspects of power production: magnesium hydride for storage, hot-spots in photovoltaic modules and arrays, reflectors for silicon alloy solar cell application, and mirror bidirectional reflectivity measurements. Other research takes up maximum power-conversion efficiency, temperature control, and the thermodynamics of radiative heat transfer in closed Brayton power cycle. A solar air-conditioning system for shaving peak electrical loads and analysis of hybrid double absorption cooling systems are also of interest [94T–105T].

Storage and Trombe walls

Because of its intermittancy solar energy utilization for continuous power and process heating necessarily involves storage. A group of reports consider aspects of storage: outside, insulated water storage tanks, rock bed storage materials, open cycle, absorption solar cooling system with solution storage, thermodynamic optimization of a sensible thermal energy storage system and storage device evaluation for solar dynamic systems.

Trombe walls are studied with respect to free convection effects, flexible analysis by computer modeling and energy management for a composite wall of porous concrete [106T–114T].

PLASMA HEAT TRANSFER AND MAGNETOHYDRODYNAMICS

Modeling for plasma characterization

The majority of the papers in this category deal with applying previously developed models to different plasma configurations, replacing equilibrium chemistry with chemical kinetics, improving expressions for the radiation heat transfer, and with description of transient phenomena. A modification of the rf induction plasma modeling approach has led to a description in which the easily measureable current in the induction coil is the input variable rather than the input power, thus allowing easier comparison with experimental data [25U]. The transition from convective energy transport to conduction at the boundary of an rf induction plasma is treated in [13U], and the insertion of a metallic tube into such a plasma has been shown to have little influence on the temperature and flow profiles in the reactor [3U]. A new model for a dc arc torch including electromagnetic forces in the momentum equation is presented in [23U], and recirculation has been found for an arc plasma flow in a converging channel due to increasing current density in the flow direction leading to the Maecker effect [7U]. A novel plasma reactor configuration has been modeled in which a plasma jet is opposed by a jet of an atomized liquid [10U]. Composition distributions for $Ar–O_2$ and $Ar–N_2$ in an rf induction plasma are obtained using a kinetic model for the dissociation [22U], and an ionization/recombination kinetics model for non-ideal plasmas is presented in [4U]. Chemical kinetics models are also presented for non-equilibrium rf discharges in N_2O [9U] and in CH_4 [17U].

The influence of using different descriptions of radiative transfer is presented for cylindrical plasmas [11U, 12U] and for a rf induction plasma [16U]. The influence of non-LTE on the Ar radiation properties is discussed in [24U] where a non-equilibrium ground state population is assumed, and in [21U] with a full collisional–radiative model. Total net emission coefficients for cylindrical plasmas in $N_2–SF_6$ mixtures are given in [6U]. Bremsstrahlung spectra in Al plasmas have been calculated with different approaches, and ranges for the applicability of the approaches are given [2U]. Formalisms for determining Bremsstrahlung in dense plasmas are given in [1U, 14U, 15U].

A new method has been developed for determining the motion of an arc under its own magnetic field by using experimentally determined magnetic field values as the input variables [20U], and a model for transient discharges e.g. after a sudden change in discharge current has been developed [8U]. Description of an arc with a superimposed axial nozzle flow using finite volume discretization is presented in [19U]. The expansion of a pulsed arc is described fluiddynamically with the arc boundary being the shock front [5U] and with a lumped cicuit model describing an overdamped arc discharge [18U].

Modeling of plasma — solid interaction

Stagnation heat transfer in a plasma boundary layer as experienced in space reentry situations has been treated by determining the effects of chemical non-equilibrium and of radiation [27U], of surface recombination [32U] and of thermoelectric and space charge processes [36U]. The influence of wall ablation on the break-up of a magnetically driven arc such as in an electromagnetic launcher has been studied [30U], and another study of ablation of arc boundaries (TFE, ice) has found that the changes of the arc characteristics can be represented by three different time constants each responsible for a different energy transfer mechanism [26U]. The heat transfer to rails of electromagnetic launchers has been calculated [41U], and the cooling requirements for repetitively pulsed launchers have been determined [33U]. Models for welding arcs include the calculation of the metal transfer using a force balance including the magnetic pressure effects with a perturbation method [35U], and a calculation of the transient heat transfer using temperature dependent materials properties [39U].

The interaction between a plasma and particles has been modeled including the effect of material evaporation with a study of the influence of different assumptions for the boundary conditions [40U], and particle charging effects [38U] and temperature gradients within the particles have been found to be important [28U, 29U]. Thermophoresis has been found to depend strongly on the sheath thickness [31U]. Particle generation through homogeneous nucleation from a gas–vapor mixture has been studied and a strong influence of charged species densities in the mixture has been found [37U]. The growth of nucleated particles through coalescence has been described using a statistical approach [34U].

Experimental characterization of plasmas and plasma heat transfer

The effect of cold gas entrainment in a plasma jet emanating into an air environment has been studied with several different diagnostic methods, and surprisingly poor mixing of the cold gas with the plasma has been found [70U]. Very short voltage pulses in high pressure Xe arcs have been explained by a finite relaxation time for the energy transfer from the electrons to the heavy particles [46U], and the influence of ablation of an insulating boundary on the arc characteristics has been investigated using spectroscopy and probe measurements [42U]. A summary of the changes in the arc characteristics for changes in the arc current is presented in [73U].

The heating and evaporation of particles flying in a plasma jet has been determined using several optical measurement techniques [56U] providing a significant advance in our prediction capability for plasma–particle heat transfer. The drag force on a sphere exposed to an Ar plasma stream has been measured and the difference to theoretical predictions discussed [81U], and drag coefficients have been measured on 100–300 μm diameter Al particles [49U]. The heat transfer from a plasma jet to a bed of granular material has been obtained by calorimetric determination of the temperature distributions [66U], and the fluid flow in a bed of particulates fluidized by a rf induction plasma and the increase in pressure drop due to the plasma heating has been determined [71U].

An energy balance of a specific transferred arc reactor configuration yielded the different heat transfer mechanisms to a surrounding wall and to the electrodes [69U], and the heat transfer from a cutting arc to the workpiece electrode has been determined for different operating conditions [63U]. A magnetic pick-up coil has been used for determining the arc motion of a magnetically driven arc [65U], and for the determination of the current density of an arc electrode attachment while the arc moved over the coil which was imbedded in the electrode surface [75U]. A comprehensive study of arc–cathode interaction for a welding arc with different cathode materials is reported [80U], in particular the erosion characteristics and surface temperatures as function of cathode material work function. An overview of arc–cathode attachment mechanisms is presented in [46U]. The interaction of plasmas generated by the irradiation of a surface with a high power laser pulse with the surface has been studied and the observed formation of erosion pits has been attributed to heat transfer non-uniformities due to instabilities [51U]. IR thermography has been used to determine the temperature distribution on surfaces exposed to plasmas [48U]. The enhancement of the heat transfer from a gas flowing in a channel to the channel walls if the gas is partially ionized by a corona discharge has been demonstrated [77U, 78U]. A new type of calorimeter has been used to measure the heat flux from an electromagnetic launcher arc to the rails [59U], and the improvement in uncertainties in plasma heat transfer measurements due to the availability of new type of calorimeters is shown in [55U]. The interaction of a nitrogen arc with an aluminum anode has led to synthesis of fine AlN powders [62U], and the formation of monodisperse powders of refractory metals in a plasma jet is described in [74U].

Radiation measurements on arcs have been performed to derive net emission coefficients for cylindrical high pressure Hg arcs [50U], and for the determination of Biberman factors for the free–bound continuum of Ar plasmas [83U]. Non LTE diagnostics applied to MPD arcs is discussed in [61U], and the influence of a plasma layer covering a metallic surface on the microwave absorption and reflection of this surface is presented in [60U].

Transient effects have been studied by determining the spectral change of the emitted radiation during a pulse discharge [45U], including the influence of chemical reactions and chemical non-equilibrium [43U, 44U]. Temporally resolved temperature measurements have been performed on Ar plasmas generated by a laser pulse [76U], and the establishment of an arc column has been found to proceed in three stages each characterized by a different dominating energy transfer mechanism [72U]. Spectroscopic measurements of a pulsed arc in a water-filled capillary tube have shown a transition from optically thin to optically thick radiation [54U]. The fluorescence of a phosphor with a selected broad band sensitivity irradiated by a plasma via a rotating mirror has been used for plasma characterization with high temporal and spatial resolution [85U], and fast changes of refractive index have been measured with an arrangement of a cw laser and a fast Si photodiode, [58U]. A new technique for Langmuir probe measurements allows correction for the disturbances experienced in rf plasmas by using a second unbiased probe [67U], and corrections for perturbation of signals from magnetic probes by the presence of the probes have been derived [53U]. Other reports of diagnostics include temperature measurements in a hydrocarbon synthesis reactor using CARS [64U], and mass spectrometric probing of plasmas containing hydrogen and carbon for carbon film deposition [68U, 84U]. An interesting new method for determining the current densities in cathode spots has been developed using the Zeeman splitting of emission lines [82U].

Descriptions of new designs of plasma sources include a large volume arc discharge with an array of small cathodes operating in parallel each with a series resistor for electrical stability [57U]. Another approach for creating a large volume discharge uses a low energy electron beam from thermionic filaments to sustain the discharge [80U]. A pulsed discharge generating a supersonic plasma jet for observation of short lived radical species is described in [52U].

MHD

This topic remains a source of theoretical studies with respect to power conversion system issues [94U, 95U, 98U, 100U, 101U] as well as with regard to specific magnetofluiddynamic effects [88U, 89U, 91U–93U, 96U, 97U, 99U, 104U–106U]. An overview of the current issues is presented in [103U]. The MHD power system studies are concerned with improved efficiency [94U, 98U], e.g. by considering separation of electricity generation from the heat transport [98U], and with transient system performance [95U] and system stability, offering linear and non-linear treatments for open cycle disk generators [100U, 101U]. A code for simulating the temperature and flow fields in a closed cycle high temperature reactor has been developed [106U], and the discontinuities of the properties at the boundaries have been considered in a model for MHD channel flows [89U]. Current collection by a cylindrical electrode has been modeled [105U], and the decay of turbulence in the flow has been analyzed [104U]. An approximate analytical solution for an MHD fluid between rotating spheres is compared with a numerical solution [93U], and stability issues are addressed by considering influences of finite electrical conductivities [99U], by analyzing propagation of discontinuities in relativistic MHD fluids [91U], and by using a non-linear wave analysis [92U]. The influence of magnetic field gradients on free convection is modeled for a magnetic colloidal fluid [88U], and modeling results for this effect are compared with experimental results [86U]. The influence of magnetic fields on free convection has also been studied for the case of a magnetic fluid in contact with a porous plate [97U], and a diagnostic method has been developed to observe the free convection patterns using flow visualization with a liquid crystal screen [102U]. The enhancement of the susceptibility for breakdown across the insulating channel walls is predicted due to non-linear temperature gradients in these walls [87U], and the increase of the electrical conductivity of a flowing combustion plasma while the droplets of the seed solution are evaporating has been demonstrated [90U].

Applications.

A special issue of the IEEE Transactions on Plasma Science is devoted to plasma applications. Invited articles review applications like surface processing [110U], thermal plasma processing [108U], bulk chemical processing using high pressure non-equilibrium plasmas [109U, 112U] in particular ozone generation using silent discharge plasmas [112U], lighting by LTE [116U] and non-equilibrium plasmas [111U], power switches [114U] and pulsed power switches [115U], and materials analysis [107U]. Articles emphasizing other applications have been referenced already in other contexts, e.g. welding [35U, 39U, 80U] and cutting [63U], plasma spraying [28U, 29U, 31U, 38U, 49U, 56U, 70U], circuit breakers [19U, 20U, 42U], reentry [27U, 32U] and electromagnetic launchers [30U, 33U, 41U, 59U].

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EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

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Bubble characteristics and nucleate boiling incipience

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