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Heat transfer — a review of 1988 literature

E. R. G. ECKERT, R. J. GOLDSTEIN, E. PFENDER, W. E. IBELE,
S. V. PATANKAR, T. W. SIMON, N. A. DECKER, H. LEE,
S. L. GIRSHICK, C. J. SCOTT, P. J. STRYKOWSKI and K. K. TAMMA

Heat Transfer Laboratory, Department of Mechanical Engineering, University of Minnesota,
Minneapolis, MN 55455, U.S.A.

INTRODUCTION

THIS REVIEW surveys papers that were published in the English language literature during 1988 covering various fields of heat transfer, including English translations of foreign language papers. The literature research was inclusive, however, the great number of publications made some selections in some of the review sections necessary.

Several conferences were devoted to heat transfer or included heat transfer topics in their sessions during 1988. They will be briefly discussed in chronological order in this section. The *AIAA Aerospace Sciences Meeting*, held in Reno, Nevada, in January included a seminar on thermophysics. An *International Seminar on Near-wall Turbulence* sponsored by the International Centre for Heat and Mass Transfer, the United Nations educational organization, and Stanford University was held on 16–20 May in Dubrovnik, Yugoslavia. Information on the proceedings can be obtained through the International Centre for Heat and Mass Transfer, Belgrade, Yugoslavia. The *33rd ASME International Gas Turbine and Aeroengine Congress and Exposition*, 5–9 June, in Amsterdam, The Netherlands, included sessions on heat transfer with unsteady effects, airfoil heat transfer and film cooling. Inquiries about technical papers should be directed to the ASME Publications Department. The *6th Italian Conference on Fluid Flow and Heat Transfer* was held on 9–10 June in Bari, Italy. Heat transfer in single and two-phase systems and in nuclear engineering as well as experimental techniques and new technologies were discussed. Information on the proceedings can be obtained from the Institute of Machines and Energy, University of Bari. The *Fourth International Symposium on Research, Development, and Application of Solar Thermal Energy*, 13–17 June, in Sante Fe, New Mexico, was organized to include invited and technical papers as well as workshop sessions. Symposium proceedings have been published and should be available from the Solar Energy Research Institute, Golden, Colorado. The *24th AIAA Thermophysics Conference* held in San Antonio, Texas, June, included sessions on gas turbine and spacecraft heat transfer, on heat pipes, two-phase flow, and radiative heat transfer. The *Tenth Symposium on Thermophysical Properties* organized by the National Bureau of Standards, 22–23 June, in Gaithersburg, Maryland, included papers on thermal diffusivity, viscosity, mass and thermal diffusion, thermal radiative properties, surface tension, interfacial transport and wetting. Papers are published in special issues of the *International Journal of Thermophysics*. The *Third Latin American Congress on Heat and Mass Transfer* was organized at Guantajuato, Mexico, 4–7 July. The *25th National Heat Transfer Conference*, 24–27 July, at Houston, Texas, was organized in poster sessions, general sessions, and open sessions. It included also an open forum and sessions on the history of the heat transfer division, which is celebrating its 50th birthday. The 1987 Max Jakob Memorial Award was presented to S. George Bankoff, who also presented a special lecture on thermodynamics and stability of thin heated films. The Donald Q. Kern Award was given to John C. Chen, who addressed the conference on "Vapor heat transfer in fixed beds". The 50th Anniversary Honors Convocation of the conference recognized past heat transfer division chairmen and personalities who contributed essentially to the development of this field. A slide presentation reviewed the Heat Transfer Division.

The *23rd Intersociety Energy Conversion Engineering Conference* in Denver, Colorado, took place on 31 July – 5 August. Proceedings are available through the ASME Publication Department. The *XXth International Symposium on Heat Transfer in Electronic and Microelectronic Equipment*, held on 29 August – 2 September in Dubrovnik, Yugoslavia, was organized by the International Centre for Heat and Mass Transfer, Belgrade, Yugoslavia. Nine sessions dealt with the subject in keynote lectures and special lectures. It was preceded by an advanced course in electronic equipment cooling. The proceedings are published by Hemisphere Publishing Corporation. At approximately the same time, the *First World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics* held 4–9 September in Dubrovnik, Yugoslavia, presented papers on natural convection, wake flows, noncircular and complex ducts, porous media, two-phase flow, pool boiling, heat transfer in reacting systems and in non-Newtonian fluids, liquid metals and gas turbines. An open forum and film and video presentations rounded off the program. Copies of the proceedings are available from Elsevier Science Publishing Company, New York.

The *2nd U.K. National Heat Transfer Conference* in Glasgow, Scotland, 14–16 September was sponsored by the Institution of Mechanical Engineers, the Institution of Chemical Engineers, and the U.K. Heat Transfer Society. Inquiries about conference papers should be directed to the Institution of Chemical Engineers.

The *7th World Hydrogen Energy Conference* in Moscow, U.S.S.R., on 25–29 September dealt in plenary lectures and poster sessions with production, storage, transmission, and use of hydrogen. Information on the lectures can be obtained at the International Association for Hydrogen Energy, Coral Gables, Florida. An *International Symposium on Combustion and Plasma Synthesis of High Temperature Materials* in San Francisco, California, on 23–26 October was sponsored by the Basic Science Division of the American Ceramic Society. The *109th ASME Winter Annual Meeting* in Chicago, Illinois, 27 November–2 December, included in its program poster sessions, symposia, and panel sessions on a large variety of basic and applied heat transfer subjects. Heat transfer memorial awards were presented to Frank P. Incropera and to Gerald M. Faeth. Larry Smarr gave a lecture on "The numerical laboratory super-computing and scientific visualization" at the heat transfer dinner. The papers presented at the meeting are collected in special volumes and are available from the ASME Order Department. A *Second National Meeting on Thermal Sciences* in Aguas de Lindola, SP, Brazil, on 6–8 December, organized by the Brazilian Association of Mechanical Sciences, included papers on turbulence, thermal properties, and heat transfer with various applications. The *5th Miami International Symposium on Multi-phase Transport & Particulate Phenomena* was presented on 12–14 December in Miami Beach, Florida, by the Clean Energy Research Institute, University of Miami, in cooperation with the International Association for Hydrogen Energy. Condensed papers can be obtained from the Clean Energy Institute.

A list of books related to heat transfer and new journals published during 1988 is presented in 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

Numerous research investigations and developments (analytical/numerical and experimental) were conducted this past year, 1988, in areas related to conduction heat transfer. Some of the primary subcategories include contact conduction/contact resistance; thermal effects in composites and multilayer media; aspects of wave propagation and pulse effects; heat conduction in fins, tubes, cylinders; investigations of effective thermal conductivities; conduction combined with convection; heat pipes and heat exchangers; methods and algorithms for effective analysis; thermal stress and thermomechanical aspects in structures and materials; and miscellaneous applications. Contributions in these subcategories are briefly summarized below.

Contact conduction/contact resistance

This subcategory remains an active area of research and much of the research concentrated on investigations encompassing fundamental understanding of the contact phenomenon and contact resistance effects. Several practical problems where these effects play an important role were attempted. Considerations include: parameter and function estimations in heat transfer with applications to the contact conductance phenomenon, recent developments in contact conductance heat transfer problems, investigation of the phenomenon of thermal contact resistance, thermal contact issues in gaps and joints, boundary effects in contact conduction and contact resistance problems, and several other applications. Both analytical and experimental papers appear in this subcategory and can be found in refs. [1A–17A].

Composites and layered media

Unlike in the past, research in composites seems to be progressing at a rapid pace. Because of their durability, capability of sustaining high temperatures (high-temperature composites), and high strength to weight ratio, the potential impact of these materials in many engineering applications is clearly evident. References [18A–28A] identify some of the research conducted in this subcategory. Typical investigations included heat flow characteristics in laminates, thermal resistance issues in composites, effective thermal conductivity and thermal representation of multilayer structures, heat diffusion and analysis issues in composites, and related applications of transient thermal effects in layered media.

Laser/pulse heating and wave propagation phenomenon

Laser and/or high energy pulse heating investigations appear in refs. [29A–32A]. These papers primarily studied methods to calculate laser heating in structures and materials, thermal response due to laser-irradiation, heat pulse measurements, and other applications involving laser induced heating effects. The propagation of thermal energy transport and the resulting thermally-induced stress wave response in structures and materials is an important concern to designers. Whereas the classical theory of heat conduction assumes instantaneous propagation of thermal energy transport (which is commonly acceptable in many practical engineering situations) modified theories accounting for relaxation of the heat flux law have been a subject matter of some intriguing research where the thermal energy transport is no longer assumed to be diffusive but propagative. Research in these areas of thermal wave propagation appear in refs. [33A–39A].

Heat conduction: fins, tubes, cylinders, spheres, and rods

Conduction heat transfer issues in bodies and in multiple objects having repetitive and/or random geometries have long been a subject matter of research interest because of the many practical situations encountered in engineering problems. Typical research issues included conduction heat transfer aspects due to effective thermal conductivity approximations, analytical/numerical and experimental investigations, boundary effects, heating conditions, optimization considerations, and steady/transient thermal analysis in objects of these shapes [40A–64A].

Conduction with convection

The papers appearing in this subcategory investigated bounds for conduction and forced convection heat transfer, heating of objects of simple geometries in fluids, and coupling of conduction with natural convection and heat conducting fluids [65A–68A].

Conduction in heat exchanger applications

A paper considered longitudinal heat conduction on thermal fields in heat exchangers [71A]. Heat pipes for ground heating and cooling are described in ref. [72A]. Miscellaneous applications of conjugate heat transfer in a thermal regenerator and heat losses from underground steam pipes are presented in refs. [69A,70A].

Methods, algorithms, and applications

The development of new methods and algorithms is important in obtaining accurate solutions and efficiency in computations. Although there is no universal consensus, nonetheless, because of the wide range of research problems involved, different approaches and formulations may be tailored to different problems to achieve both accuracy and effectiveness in solutions. Typical research papers deal with development of effective algorithms and solution procedures, improvements in model formulations, and the like [73A–84A].

Interdisciplinary thermal–mechanical problems

Interdisciplinary thermal–mechanical problems are an important concern to the designer from the point of reliability, durability, and integrity of the structure and/or component. Research papers in this subcategory considered thermal stress issues in structures and materials, thermoelastic formulations, thermally induced elastic disturbances in solids, and other related applications [85A–96A].

Inverse

Inverse heat conduction problems and related issues have been a subject matter of quite some interest, especially, amongst the research community. Practical applicability of these is still an area of research investigations, although, some of the advantages of such developments have been documented in past literature. Related studies in this subcategory appear in refs. [97A–103A].

Miscellaneous conduction studies and special applications

Numerous miscellaneous problems and unique applications concerning thermal conduction heat transfer issues have been investigated for a varied class of problems. Since it is beyond the scope of this review to identify each contribution, readers are encouraged to see the pertinent references available in refs. [104A–135A].

CHANNEL FLOW

Forced convection in straight walled circular and rectangular ducts

Forced convective heat transfer in ducts of circular and rectangular cross-section operated under fully developed flow conditions was addressed frequently in the literature; the turbulent flow regime dominated this collection of research [1B – 16B]. A variety of initial and boundary conditions were investigated including modified Graetz–Nusselt problems, variable external heat transfer coefficients, incorporation of axially and radially dependent rates of heat generation as well as the influence of Prandtl number and fouling factor. Complicated axial variations in wall heat flux and heat generation rates were discussed for fully developed laminar flow conditions.

Mixed convection

Mixed forced–free convection was beautifully treated under an array of experimental and numerical configurations [17B – 27B]. An ensemble of changing fluid and thermal phenomena accompany the mixed convection problem of fluid flow in a vertical duct. Combinations of heated and cooled walls and asymmetrically applied temperature fields at low Reynolds numbers resulted in enhanced heat transfer rates and reverse flow. The orientation of the duct in the gravity field is central to these mixed convection problems as elucidated in several of the studies.

Conjugate problems

The conjugate heat transfer problem involving two-dimensional wall conduction effects on convective heat transfer was treated numerically [28B – 33B]. Radial and axial wall conduction cannot be neglected (for relatively thick walls) for high Peclet numbers, conditions of high wall-to-fluid thermal conductivity ratio and short heating lengths; neglecting the wall conduction leads to underestimation of convective heat transfer rates. Investigators also computed the wall conduction effects in the presence of externally attached fins.

Entrance effects

The hydrodynamic and thermal entrance regions were computed numerically for ducts of circular, square, rectangular, annular, and rhombic cross-section [34B – 42B]. The boundary conditions employed were typically for an isothermal wall or a wall with constant heat flux. Only a small minority of the computations analyzed the full three-dimensional laminar flow field. Mixed forced–free convection was computed for horizontal and inclined ducts of circular and rectangular cross-section. The inclination angle was varied along with combinations of upper and lower wall heating. The laminar entrance region of a circular pipe with longitudinal internal fins was also analyzed.

Irregular geometries

Channels consisting of wavy parallel walls (S-shaped centerline) experience enhanced heat transfer rates compared to straight walled ducts under identical pumping power and mass flow rates; a reduction in heat transfer rates is observed when both are operated under identical pressure drop conditions. Heat transfer characteristics are documented for a variety of channel widths and boundary conditions including constant enthalpy boundary conditions. Periodically converging–diverging channels were also analyzed for both circular and annular cross-sectioned ducts. The geometries (wavelength and amplitude) were parametrically varied to optimize heat transfer rates without excessive pressure drop penalties. Several investigations considered the fully developed flow in straight annular ducts of circular and elliptic cross-section as well as straight ducts with elliptic and semi-circular cross-section [43B – 58B].

Finned passages

A variety of numerical and experimental studies were devoted to channel studies where geometric nonuniformities were employed to augment the heat transfer rates [59B – 72B]. To simulate the cooling passages of turbine blades, rectangular ribs were placed along a channel wall in an orientation either normal or at various angles to the oncoming flow. Rectangular fins were also placed on the inner surfaces of annular passages to affect the heat transfer rates on the opposite heated walls, an arrangement common in nuclear design. In most investigations heat transfer enhancement was addressed together with associated alterations in friction factor or overall system pressure drop. Two- and three-dimensional arrangements of rectangular blocks were investigated to model the coolant flow through electronic equipment under fully developed flow conditions and in entrance regions. Horizontal 'boards' were studied with heated rectangular elements oriented both upwards and downwards; mixed forced–free convection was analyzed. Detailed measurements of isolated protruding elements elucidated the effect on heat transfer rates of local separation and reattachment regions; a second law thermodynamic analysis was performed to optimize the design of a single protruding fin.

Secondary flow

Fluid flow in ducts encountering centripetal acceleration — flow around corners, bends and in helically coiled pipes — experience strong secondary motion in laminar, transitional and turbulent regimes; in fact under some conditions relaminarization occurs. This secondary motion provides an ensemble of fascinating heat transfer problems which can either enhance or reduce local heat transfer rates depending on the magnitude of the Dean number. In helically coiled circular and annular ducts, increasing pitch angle significantly increases buoyancy effects thereby enhancing heat transfer rates. Numerical simulations have addressed both the laminar and turbulent regimes in bends, however with some difficulties in correctly modeling the non-isotropic turbulence. Secondary flow recovery has been investigated in straight ducts by generating swirl upstream of the straight section or by placement of the straight section downstream of a bend or coil. In the range of Reynolds numbers investigated the heat transfer rates were enhanced by secondary flow and buoyancy [73B – 86B].

Non-Newtonian fluids

Many practical and challenging problems were investigated in the literature involving non-Newtonian fluids [87B – 94B]. The flow of animal blood in a centrifuge was modeled using a Taylor–Couette apparatus with a micropolar fluid; temperature and velocity distributions were computed numerically. Heat and mass transfer properties of beef cattle manure slurries transported in an annular tube were compared against available power-law fluid data. Food extrusion processes required solving the Graetz–Nusselt problem of a power-law fluid with viscous dissipation. The thermal developing regions were computed for a range of power-law fluids, polymer solutions and rarefied gases.

Two-phase flow

Heat transfer rates in fluid–solid mixtures can be optimized by careful control of particle size and shape, particle thermophysical properties and flow Reynolds number. Gas–solid mixtures of air–glass, air–lead and air–dust, and a liquid–solid mixture of water–feldspar were analyzed. Particular attention was given to the suspended-particle / wall-interaction and the associated heat transfer augmentation. The influence of air bubbles on the heat transfer rate from water flowing in a narrow vertical channel was also investigated [95B – 102B].

Miscellaneous

The temperature fields and heat transfer characteristics were computed for the fully developed axial flow through rod bundle sub-channels; tubes were of circular, rectangular and triangular cross-section. Thermal effects were studied in journal bearings under radial and axial loading and a rotating Couette apparatus was used to study the solidification of tin. Fluid turbulence and heat transfer were modeled under buoyant and non-buoyant conditions in a spherical annulus. The properties of pressurized and saturated He II were investigated under steady and transient circumstances; the Joule–Thompson effect was analyzed in turbulent He II flow. The influence of recycle on overall heat transfer performance was investigated in a concentric tube and a rectangular channel. Flow in cavities was studied in two dimensions for a situation with a single translating wall, and in three dimensions for flow in the neighborhood of a local hot spot [103B – 118B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Laminar

Surveys are given of methods of analysis of convective heat transfer in external flows [27C, 91C]. High velocity effects are described, such as radiation effects for hypersonic re-entry [14C]. Laminar stagnation region analyses include such effects as unsteady three-dimensional flows [46C, 47C, 96C], low Reynolds numbers [28C], unsteady effects with magnetic fields [45C], periodic boundary layers on circular cylinders [25C], and the final approach to steady state in a non-steady axisymmetric stagnation point [24C].

A note is given on Prandtl's transposition theorem [94C]. Reference [22C] studies the analogy of convective processes with different bulk sources [22C]. Approximate formulas are given for low Prandtl number wedge flows [3C], and for non-steady convection with vanishing Prandtl number [52C]. Three papers [32C, 54C, 77C], analyze mixed-convection boundary layer flows. A reversed-flow singularity in interacting boundary layers is discussed [75C]. Non-steady effects examined include resonant flow in small cavities [5C], an oscillating flat plate [48C], heat-wave excitation in a density gradient [57C], oscillation of gas columns [62C], g-jitter [65C], and a continuously stretching surface [7C, 8C, 26C, 49C]. A stretching sheet in hydromagnetic flow [16C], and hydromagnetic convection at a continuous moving surface [86C], complete a list of interesting surface effects.

There is an anomalous effect of surface temperature on the stability of a laminar boundary layer [50C]. Two papers on vortices in boundary layers describe non-linear Gortler development [29C] and non-steady cross-flow vortices [6C]. Nine papers on the flow around cylinders [30C, 34C, 78C, 79C], discuss cylindrical forced–free flow [87C], cylinders with vortex generators [36C], elliptic cylinders in tandem [64C], infinite square arrays [41C], and random arrays of cylinders [70C]. Flows around spheres involve rarefied monatomic flows [67C], rarefied polyatomic flows [66C], power-law fluids [90C], and spheres submerged in water and bubbling jets [38C]. Other geometries studied include parallel plate walls [95C], and convex target surfaces [93C]. Micropolar fluids with suction or injection are also examined [2C, 91C].

Turbulent

Turbulence mechanisms continue to receive attention. Wave instabilities of a Taylor vortex flow [60C], variational turbulent transport equations in highly unsteady processes [74C], flows with large- and fine-scale turbulence [18C], analysis of penetrating turbulent convections [97C], the size of turbulent wall eddies [53C], the influence of initial conditions on the rate of damping of temperature fluctuations [4C, 73C], and flow of high molecular weight polymers [43C] are a few of the turbulence effects considered. A statistical approach to turbulence is revealed [15C, 50C, 80C]. Additional effects examined include the axisymmetric spreading to an underlying fluid by material on the surface [89C], the effect of freestream turbulence on plate flow [76C], favorable pressure gradients [19C, 42C, 51C], variable physical properties [1C, 12C, 88C], and profiles on turbine blades [63C, 84C]. Other turbine related papers include refs. [23C, 44C, 68C, 69C, 92C]. The wake function method is recalled in ref. [10C]. The k–ϵ model is applied to gas-stirred baths in ref. [71C]. Two equation models are still popular [58C].

A second law analysis is given for heat transfer enhancement on a rib-type turbulence promoter [9C, 81C], and fins [21C]. Two-phase turbulent flows studied describe the analogy between heat and mass in the turbulent two-phase regime [13C], air–water mist flows [20C, 55C], spray cooling of a hot surface [39C], liquid flow analyses in evaporator grooves of a cold plate [33C], numerical modeling of the atmosphere boundary layers over the ocean [40C], and latent heat recovery from turbulent flue gases [82C, 83C], wavy falling films [72C], and heat exchange at the surface of an irrigation cooler [56C].

FLOW WITH SEPARATED REGIONS

Separation: cylinders

The rich detail accompanying the separated viscous flow over cylinders has attracted the attention of researchers qualitatively since the days of Leonardo da Vinci and quantitatively at least since the measurements of Strouhal. The associated thermal aspects of this problem are equally stimulating and have received considerable attention in the literature [1D – 13D]. A collection of experimental and numerical work has analyzed the nominally two-dimensional flow past cylinders of circular, square and triangular cross-section.

Local unsteady heat transfer characteristics have been documented in detail in the neighborhood of flow separation. Small aspect ratio cylinders were studied between confining walls to model the flow past fuel elements of gas-cooled reactors; enhanced heat transfer rates were generated by the wall–cylinder horseshoe vortices. Short cylinders were also placed in the core region of a heated turbulent jet to simulate burner rig test targets. The flow past a circular cylinder held parallel and adjacent to a wall was analyzed experimentally; the heat transfer rate was minimized when the wall-to-cylinder spacing was eliminated. The heat transfer from a triangular cylinder was investigated under hypersonic flow conditions. Multiple cylinder configurations were studied, including a tandem arrangement of elliptic cylinders, in-line and staggered tube bundles with fins and a scheme to optimize heat transfer/friction factor behavior using eddy promoting cylinders. The self-similar turbulent far wake was also studied by quadrant analysis.

Separation : steps and cavities

Regions of flow separation, recirculation and reattachment can be expected whenever a nominally parallel flow encounters a rapid geometric change; common configurations include the backward facing step and cavities [14D – 23D]. Unsteady laminar flow has been simulated numerically to determine the instantaneous and time-averaged heat transfer characteristics in the neighborhood of flow reattachment. Experimental and numerical investigations have considered the higher order turbulent temperature–velocity products in an attempt to explain the displacement in the location of maximum local Nusselt numbers and flow reattachment. The cavity created by an annular recess on a sharp cone with and without gas injection was analyzed experimentally under hypersonic conditions; a survey of separated supersonic and hypersonic flows was presented. The axisymmetric melting cavity of a cylinder generated by an annular heating ring was studied; the melting and freezing process depends on the magnitude of the secondary flow in the cavity.

Separation : miscellaneous

Turbulent jets were investigated both as they issued into a large quiescent environment and as they developed downstream of a sudden expansion. In the former case the momentum and heat transfer processes are dictated by large structure dynamics and in the latter by a strong recirculation region. Upward and downward directed heated laminar jets were studied as they impinged on a flat plate held normal to the oncoming stream. Entrainment was investigated experimentally as gas bubbles rise in an immiscible liquid. Temperature fluctuations were measured downstream of the recirculation region formed on the leading edge of a blunt-edge plate. A survey was presented which addressed two broad classes of flows which do not conform to boundaries, those experiencing centripetal acceleration or buoyancy and those undergoing separation. Journal bearings were investigated under conditions of reverse flow and cavitation [24D – 30D].

HEAT TRANSFER IN POROUS MEDIA

Heat transfer in packed beds

A large variety of important processes involving forced flow through a porous solid or a collection of particles provide impetus to furthering our understanding of the heat transfer in such systems. Several articles [1DP – 21DP] lead in that direction. General models, emphasizing entry length heat transfer, the effects of fluid dispersion, and transient behavior, as well as specific applications, ranging from the design of chemical reactors to the estimation of cooling of disabled nuclear reactors, have been investigated. Other general models, focused on non-Darcy flow behavior, have also been explored and are treated in a later section.

Heat transfer in fluidized beds

Many papers [22DP – 44DP] were produced concerning fluidized beds, which may be considered to be moving porous media, and which also offer unique process opportunities, but which have generally been less successfully modeled. Detailed observation and fundamental modeling, particularly of the heat transfer to and from immersed horizontal cylinders, were reported. The gas phase component of convective heat transfer to immersed surfaces was examined. Reports were also made of analysis and experimentation with special cases of fluidized beds: beds used as combustors, beds with frost on surfaces, beds proposed as heat exchangers for Stirling engines, shallow beds for use as heat exchangers, beds with mobile (free-floating) internals, and beds with overall solid flow in the horizontal direction.

Combined heat and mass transfer in porous media

Many reported studies dealt with the simultaneous transport of heat and mass in porous media [45DP – 64DP]. Several papers reviewed and refined the underlying fundamentals of combined heat and mass (or, more specifically, moisture) transfer. The drying of granular products and the thermal modeling of moist soil were each the topic of a few articles. Other subjects included internal evaporation induced by laser irradiation and vacuum sublimation.

Natural convection in porous media

A large number of reports [65DP – 85DP] relayed treatments of natural convection in porous media; while a small number provided experimental approaches, most employed numerical and/or analytical techniques. Generally, each explored the particular behavior induced by special geometric shapes or boundary conditions. Media within rectilinear boundaries inclined with respect to gravity were the subject of three articles. Systems with permeable boundaries were analyzed, as were boundary conditions of specified heat flux, and the consequences of a temperature range encompassing a liquid's temperature of maximum density.

Mixed convection in porous media

Analysis and numerical evaluations were presented for several geometries and boundary conditions in which the combined effects of forced and natural convection were expected [86DP – 94DP]. Only one of these studies added new experimental evidence to the literature.

Instability

Thermal instabilities and the onset of natural convection flows in porous media were treated in a few diverse papers [95DP – 100DP]. Specific topics ranged from the instabilities in inclined boundary layers to the thaw of subsea permafrost.

Non-Darcy effects in porous media

Effects absent in the widely-used Darcy model of flow through a porous medium include viscous friction at bounding surfaces and the fluid inertia component of fluid/medium momentum exchange. Some papers in preceding sections addressed these departures from the Darcy model, but several more [101DP – 110DP] were directed toward the disparities between heat transfer predictions based on the Darcy model and those founded on more complex models incorporating non-Darcy effects. Most of these were analytical works, with only two adding experimental findings.

Other porous media studies

A large number of porous media heat transfer studies fail to readily fit a simple scheme of categorization [111DP – 127DP]. One suggested a unifying theory of transport phenomena in fixed, fluidized, and sparse particulate systems, keyed to the void fraction. Several dealt with special heat exchanger designs such as a counterflow of small particles downward through an upward gas flow in a packing of larger solids, a packed bed cooling tower, a curtain of solid particles falling freely through a gas, and vibrated beds of solid particles flowing past heat exchange surfaces. Several more articles dealt with applications to very specific processes such as sterilizing of canned beans, the thermal aspects of hydriding and dehydriding a metal hydride bed, and the heat transfer in flow through naturally fractured reservoirs.

EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

Temperature measurement

The measurement of temperature still relies heavily on thermocouples and a considerable number of papers discuss their fabrication [21E], testing [6E], time response [15E, 29E], and possible errors [2E, 22E]. Their use is considered for various applications like bioengineering [lE, 22E], combustion [8E], in soils [19E] and in flight [9E].

Optical methods using the interferometer [4E, 28E], spectroscope [14E, 24E], and Rayleigh scattering [23E]. Fiber optics for temperature measurements are found in refs. [13E, 17E, 26E].

Velocity measurement

Velocity measurements rely heavily on hot wires [30E – 33E, 37E]. The use of lasers is discussed in refs. [34E – 36E, 42E, 45E, 46E]. Papers on mass flow meters [39E, 55E] include silicon flow sensors [53E]. Pitot tubes were used in fluidized beds [49E].

Heat flux measurement

The measurement of heat flux considered use of film gages [59E, 63E], also for high temperatures [67E]. Color change paint is used to measure convective heat transfer coefficients [61E]. Another method to obtain local heat transfer coefficients is described in ref. [68E]. A radiometer was used for the study of aerodynamic heating [60E].

Humidity measurement

A device for the measurement of local humidity uses optical fibers [69E].

Flow visualization. Flow visualization with color schlieren is reported in ref. [70E].

Properties measurement

The measurement of various properties considers particulate materials [71E, 74E], polymer glasses [78E], transparent fluids [104E, 107E], composite materials for space applications [86E], tissue surfaces [94E], soils [98E], drop size distributions [83E], and void fraction measurements [103E]. The density distribution in boundary layers is also considered [105E].

NATURAL CONVECTION — INTERNAL FLOWS

Introduction

Buoyancy driven convection in enclosures continues to be of major interest to researchers in a variety of engineering and scientific disciplines. Research reported in the last year covers such fields as applied mathematics, basic physics, astrophysics, meteorology, fundamental engineering fluid mechanics, etc. with subject areas such as consideration of non-linear phenomena, transformations to chaos and turbulence, as well as applications ranging from manufacturing of crystals to solar energy receivers, and heating and ventilating of buildings. The papers included are grouped in various categories with potential overlap of interest of the authors and the prospective readers.

Horizontal layers heated from below

Convection in a horizontal layer of a single fluid heated from below has been of interest to researchers for almost a century. Generally called Rayleigh–Benard or Benard convection, it covers a wide range of potential flow geometries with great appeal to researchers interested in stability and transition to various types of unsteady flows including chaos and turbulence [1F–20F]. Several studies consider the initial transition to a steady flow including the resulting planforms and phenomena that occur at low Rayleigh number. The influence of such parameters as side-wall geometry and variable properties have been considered. Some experiments used optical techniques to analyze planforms and determine velocity distributions. At higher Rayleigh number, interest is directed toward the flow patterns and overall heat transfer.

Overlaying fluid layers

Both the initial transition to flow and the flow patterns in overlaying layers of fluids, i.e. one on top of the other, are closely related to flow in a single layer but with a number of complications. Analysis as well as measurements of the velocity pattern and heat transfer including the effect of a slight inclination of the layers and the potential of an oscillatory onset of convection have been reported [21F–25F].

Internal energy sources

Internal energy sources in a fluid layer can come from such natural phenomena as radioactive decay, electromagnetic radiation absorption, chemical reactions, Joule heating and others. Flows with such energy sources [26F–31F], though of similar nature to flows driven by temperature differences across a layer, show somewhat different transitions and flow characteristics in both steady and transient situations.

Double-diffusive flows

Convective flows driven by buoyancy differences result not only from temperature gradients, but also other differences such as in concentration. When two different gradients influence the density distribution, and therefore the buoyancy in a body force field, we call the resulting flow a double-diffusive flow. A number of studies [32F–38F] consider such systems, both analytically and experimentally. Flow patterns have been measured, the dynamics have been analyzed and several theorems have been developed to describe these special flows.

Marangoni or thermocapillary flows

In addition to temperature distribution or concentration differences, capillarity or surface tension effects can also drive flows when there is a variation in surface tension along an open surface of a fluid or at a fluid–fluid interface. Often this difference is due to temperature gradients and the flows are called thermocapillary flows or Marangoni flows, after an early researcher in this area. Research on such flows has been reported [39F–51F] for systems as divergent as liquid metals and high Prandtl number fluids; fluids in shallow layers of a melt and for a number of systems aimed at analyzing growth of crystals. Stability studies of such flows and the influences of external effects such as magnetic fields have also been considered.

Vertical slots and tubes

Many works [52F–71F] report on flows in vertical slots and tubes including laminar flows, transition, and turbulent flows. The influence of asymmetric heating, cross-section geometry of the tube, variations in gravitational force, power-law fluids, bifurcation phenomena, and instability in such flows are considered.

Differentially heated layers

In a number of enclosures, often those of significant horizontal extent, a horizontal temperature gradient due to a temperature difference imposed between vertical boundaries can give rise to a number of different convection phenomena. The influence of vertical partitions, roughness on a vertical wall, transient boundary conditions, and inclination of a layer, all have significant effects on the flow and heat transfer rate [72F–91F].

Annuli, spheres, and other geometries

Convection in the fluid held between two cylinders, one within the other, or in a cylinder with a non-uniform temperature on the boundary, have been examined including the influence of baffles, eccentricity, and low temperature phenomena. Similar phenomena in spherical and hemispherical cavities, and in chambers with a trapezoidal shape have been studied with predictions from numerical simulations and some experiments [92F–112F].

Thermosyphons

Thermosyphons or natural convection circulation loops are driven by temperature differences between two vertical sections of the loop, which provide differences in density and buoyancy. The influence of cross-section, gas concentration, and stability of such loops have been examined [113F–118F].

Porous media

The flow equations in porous media differ from those in a free fluid. The influences of inclination, mixed convection, layers only partially filled with porous material, and micropolar fluids on buoyancy driven convection in such media have been studied [119F–124F].

Mixed convection

In mixed convection, the flow arises not only from buoyancy forces, but also from forced motion of the fluid. The relative importance of the buoyancy driven flow compared to the forced flow is a function of the parameters describing the flows. Mixed convection has been studied in a variety of systems [125F–131F]. The influence of tube geometry, tube orientation, presence of a shrouded fin and convection in an unsteady flow have all been considered.

Miscellaneous applications

A number of studies on buoyancy driven flows [132F–148F] do not quite fit in any of the categories listed above. Such studies include convection in solar collectors, applications in liquid helium, influence of electric and magnetic fields, interaction of convection with thermal radiation, and heat transfer in a number of applications in manufacturing and solidification.

NATURAL CONVECTION — EXTERNAL FLOWS

Natural convection lends itself to analysis or computation because the flow involved is usually laminar or in the early stages of transition. Approximately two-thirds of the papers in this section are, therefore, analytical and the rest experimental. The analysis transforms boundary layer equations into a self similar form [15FF] or in integral form [22FF], obtains exact solutions [41FF] or series expansion [77FF]. Experiments are often carried out to compare the results with those obtained by computation [16FF]. They are amplified by visualization [10FF]. Turbulent shear ($\overline{u'v'}$) and turbulent heat flux ($\overline{u'T'}$) were measured [46FF].

Heat transfer

Most free convection studies are concerned with those driven by temperature differences and causing heat transfer. Numerous geometries have been studied: vertical plates with ribs or partitions, vertical cylinders, inclined plates, horizontal bars and cylinders, spheres at low Grashof number, spectral segments and flow near corners and wedges.

A paper includes also the effect of magnetic forces [1FF]. Micropolar fluids [8FF] and water near maximum density [12FF] have been studied.

Boundary conditions include variable temperature, blowing and suction at a horizontal plate [14FF], concentrated and distributed heat sources, and stratification of the external medium.

Mass transfer

Combined heat and mass transfer is reported between inclined plates and on conical surfaces.

Plumes

A number of papers are concerned with axisymmetric laminar and turbulent heat and mass transfer in plumes. Two of them study the influences of second-order effects [36FF, 37FF].

Mixed flow

The paragraph on mixed flow includes papers on convection on horizontal cylinders and spheres, on vertical and inclined parallel plates, on vertical tubes in turbulent flow and on stagnation flow. The vortex generation above horizontal heated plates is covered in ref. [44FF] and micropolar fluids are investigated in ref. [39FF].

Turbulence and instability

Results of turbulence on heat transfer can be found for flow on vertical plates and cylinders. The spectra of the temperature fluctuations were measured in ref. [49FF].

Flow instability and transition to turbulence are reported for horizontal plates, and horizontal cylinders. The analyses use perturbation, steady wave instability, fundamental models in plain plumes, and the transition to turbulence, and map the various free convection regimes [58FF].

Unsteady flows

Unsteady convection includes transient heat transfer on an impulsively started vertical plate, convection generated by periodic heat input, and boundary layer development caused by a moving heat line.

Porous media and suspensions

Non-Darcy convection in a porous medium generated by a horizontal line of heat or on vertical or horizontal plates has been reported.

Change of phase

Change of phase is considered under condition of melting or freezing, inside of weld pools, and in molten silicon.

Variable properties

The influence of variable properties on natural convection heat transfer is covered for power-law and non-Newtonian fluids, for those with temperature-dependent viscosity, and for water at 4°C.

CONVECTION FROM ROTATING SURFACES

A number of experimental and theoretical investigations involving rotating surfaces were reported. The work involved different geometrical configurations, laminar and turbulent flow, and heat and/or mass transfer.

Rotating disks

Flow and heat transfer on rotating disks were studied [1G–5G] via experimental measurements and theoretical calculations. The situations contained combinations of stationary and rotating disks appropriate to gas turbine configurations.

Rotating cylinders, spheres, and cavities

A number of papers report work on various rotating configurations [6G–13G]. These include rotating concentric cylinders, ducts, spheres, etc. The effect of buoyancy is considered in some studies, while correlations for heat transfer are provided in a few places.

Other rotating flows

Turbulence, condensation, convection in binary mixtures, and the corresponding stability are considered in refs. [14G–17G].

COMBINED HEAT AND MASS TRANSFER

Introduction

Combined heat and mass transfer including jet impingement systems were examined in a wide range of studies in the past year. There has been considerable activity related to transpiration, ablation, film cooling, jet impingement heat transfer, drying, and a number of combined mass and heat transfer systems.

Transpiration and ablation

In transpiration cooling a surface is protected from a hot stream flowing over it by a more or less uniform flow of coolant transpiring through the surface. In other systems suction through a wall occurs, though not to protect the surface from the flow over it. There are similarities in the analysis and measurement of the heat transfer with blowing or suction. A related flow occurs in ablating systems where, rather than blowing through a surface, the material that the surface is composed of goes into the boundary layer by a combination of evaporation, spalling, and other processes (driven by the high temperature and shear of the flow over the surface). This produces a fluid and particle flow near the surface which reduces the temperature in the boundary layer. A number of studies considered transpiration, including suction, and ablation in the past year [1H–8H]. Studies of supercritical injection, presence of power-law fluids, asymptotic solutions, angled injection, and use of composites were reported.

Film cooling

With film cooling, a fluid (usually a gas) is injected at one or more discrete locations along a surface into the boundary layer of the fluid flowing over the surface. The coolant essentially acts as a heat sink to lower the temperature in the boundary layer of the fluid flowing over the surface, thus reducing the heat transfer to the surface. Studies on film cooling [9H–20H] include applications to gas turbine systems, use of full coverage film cooling (where a large number of small holes are on the surface) influence of density ratio (injected fluid to the mainstream fluid) and variations in the injection hole geometry.

Jet impingement

The high heat transfer possible with impinging jets [21H–29H], makes this an attractive area for study as well as eventual application. The influence of angle of inclination of the jet, dimension of the heating surface, cross-flow of a stream, and perforation in a plate on impinging surfaces have been examined. Multiple slot geometries including individual holes and two-dimensional slots, and both velocity and pressure fluctuations near the surface have also been considered.

Mist (spray) cooling

Liquid droplets, carried along in a gas stream that impinge on a surface can produce relatively high rates of heat transfer. Applications in tempering of glass, means of predicting spray cooling, as well as the influence of boundary conditions on the fluid mechanics and heat transfer have been reported [30H–34H].

Drying

Drying systems have been considered for surfaces of different geometries and different materials, including grains and wood. Experimental and mathematical models have been applied to predict drying under a range of conditions [35H–38H].

Simultaneous mass and heat transfer

A pot-pourri of subjects on heat and mass transfer [39H–46H] include application of a finite-element approach, modeling mass transfer from a sphere, calculations for different geometries of disks, evaporation from open cavities, absorption, etc. In some cases, simultaneous heat and mass transfer is analyzed numerically; others measure heat and mass transfer over a range of experimental conditions.

CHANGE OF PHASE — BOILING

Boiling heat transfer remains an active research and application topic with over 170 papers presented in 1988. The boiling section has been subcategorized into eleven subsections according to the main emphasis of each paper. Liquid/vapor change of phase papers may also be found in categories JJ (Change of phase — condensation) and S (Heat transfer applications — general).

Pool boiling

Pool boiling papers focused on such effects as subcooling, orientation, surface finish, measurement techniques specific to pool boiling tests and the special nature of particular fluids [1J – 13J]. Many of these papers were oriented around cryogenic fluids used for electronic, superconducting or magnetic system cooling using nitrogen or helium. Others were carried out with the dielectric fluids which have been specially designed for cooling of electronic equipment at near-atmospheric temperatures. Many focused on the prediction of the critical heat flux (CHF).

Forced convection boiling

This first subcategory of forced convection boiling addresses the processes present in the nucleate boiling regime [14J – 30J]. Internal forced convection boiling papers dealt with such issues as boiling under various two-phase flow regimes, effects of particles suspended in the flow, channel orientation, fins or ribs, flow acceleration and gases dissolved within the liquid. In several papers, forced convection boiling in channels which are very narrow relative to bubble sizes was studied, with application to cooling of electronic equipment. Many investigated the accuracy of existing nucleate boiling correlations for various applications. External forced convection boiling papers were on tubes in cross-flow, including augmentation due to nearby, rising bubbles.

Forced convection boiling critical heat flux

The second forced convection boiling subsection focuses on CHF [31J – 45J]. Internal forced convection CHF papers dealt with the effects of flow regime, transients in power, narrow spaces, centrifugal fields and large length-to-diameter ratio. Applications included fission and fusion reactor cooling systems. External flow papers were concerned with CHF of cylinders in cross-flow.

Post-CHF heat transfer

This topic refers to post-CHF heat transfer or film boiling [46J – 70J]. Post-CHF pool boiling papers showed results of studies on the effects of surface orientation, subcooling, droplet impingement upon a vapor film and conjugated heat transfer due to wall conduction. Several papers dealt with special behavior of superfluid helium and cryogenic fluids. Several others studied the quenching of spheres and cylinders in a liquid pool. Some dealt with the stability of the flow under film boiling and the stability of the vapor film.

Post-CHF forced convection heat transfer papers discussed the effects of flow rate, subcooling, inlet flow conditions and channel geometry (including bundles of tubes). One investigated flow oscillations which may appear in film boiling. Another showed the behavior on a porous surface. Several tested correlations for computing the film boiling heat transfer coefficient or criteria for determining transition.

Transition boiling, reflooding and rewetting

Effects studied under the rewetting category were liquid–solid contact, complex geometry, hysteresis and contact angle [71J – 84J]. Several papers applied to heat exchangers. Others investigated the quenching of molten fuels or core debris or the reflooding and quenching of fuel bundles, as in reactor accidents. Several critiqued rewetting models. One applied to rewetting with falling films and another investigated the rewetting of a spinning disk with impinging drops. A special heat transfer test section for rewet measurements was described.

Incipience and bubble growth

Some papers were written on the process of incipience, the initiation of nucleate boiling [85J – 91J]. Effects discussed were orientation of the surface, surface geometry, velocity, channel size, stability of a vapor pocket within a surface cavity and nucleation free surfaces. Special consideration was given to highly-wetting fluids such as refrigerants and dielectric fluids used in the cooling of electronic equipment. One study compared a number of nucleation processes, including crystal growth. Another dealt with nucleation on clean glass surfaces.

Fundamentals of surface boiling

These papers were specifically on the fundamental processes which occur during boiling [92J – 103J]. Special processes which were investigated include bubble growth, condensation, interaction of one site with another, dissolution of vapor and gas bubbles, microlayer evaporation, transient heating, fluid/surface wetting angle, unsteadiness and high subcooling. A model for nucleation site density in terms of surface characteristics was given. One paper presented a quantum field theory of phonons and boiling in liquids. Another presented a detailed description of burnout processes for heated, horizontal cylinders.

Enhancement techniques in surface boiling

Enhancement techniques which were documented include metal-spraying the surface, coating with polyurethane and other porous materials and impinging with an electro-hydrodynamical liquid jet [104J – 112J]. For internal surfaces, knurling, threading and mounting of spiral ribs were tried. One study documented the performance of a modified GEWA-T boiling surface.

Sprays, mists and droplets

This subcategory includes papers with droplet mists and sprays [113J – 121J]. Papers with external surface heat transfer showed the effects of cooling a wedge or a cylinder in a mist flow and impinging or falling droplets on the vapor film thickness. An internal flow situation had cooling with jets spurted in a narrow space.

Film evaporation

A large number of papers was presented on the topics of film evaporation, surface evaporation and evaporators [122J – 145J]. Many were presented on boiling and vaporization in falling films and wetted-wall columns; effects under study included development length, laminar versus turbulent flow, critical thermal flux (critical heat flux), incipience and supercritical fluid behavior. A variation on the falling film was film evaporation in a rotating channel. In evaporator tube studies, effects such as, circumferentially non-uniform heating, scaling in size and enhanced surfaces were considered. Geometries peculiar to the thermosyphon were discussed. A model for surface drying based on molecular motion between two fluid phases was presented. Papers were given on the evaporation of droplets near a surface and in an expanding jet and evaporation in partially-filled tubes and cavities. Laser-induced evaporation was discussed in one paper. Models for an evaporating meniscus and for a falling film evaporator were presented.

Free vaporization

This subcategory includes phase change processes across a free interface (not attached to a wall) [146J – 170J]. Free vaporization studies for internal flows included modeling of turbulence effects on droplet evaporation, evaporation of droplets and spray in air and air/steam mixtures, sprays emerging from a water jet, direct contact heat and mass transfer from a bubble and homogeneous vaporization in bubble chambers. Effects studied in single-drop evaporation included large Knudsen numbers, variable properties and internal circulation. Studies in pools included explosive boiling of a liquid droplet, or molten UO_2 in sodium, evaporation of R113 on a water surface and evaporation off a free surface below an air stream. Enhancement of vaporization was effected by utilizing surface dilation viscoelasticity and by employing an electric field. Evaporation processes at the superheat limit, at elevated pressures and in helium-4 were investigated. Heat transfer across the liquid/vapor interface during rapid depressurization and the growth of gas bubbles in a region of low pressure were discussed.

Binary mixtures and boiling in porous beds

Papers which specifically focus on binary mixtures and boiling in porous beds are listed separately [171J– 174J]. Those on binary mixtures deal with hydrocarbon/water and R11/R114 systems. One porous bed paper investigates heat transfer in nuclear reactor post-accident debris beds.

CHANGE OF PHASE — CONDENSATION

Research in this area includes a number of important aspects: effects of non-condensable gases; non-steady state condensation, geometrical influences; external and surface effects; theory and analysis; experimental measurements; laminar film condensation; and droplet condensation.

Non-condensable gas effects

The investigations of this influence embrace the estimation of air in steam–air mixtures, the further study of vapor condensation from vapor–gas mixtures and the report of steam–air mixture condensation in horizontal annular flow [1JJ–3JJ]. Effects of noncondensables in a thermosyphon, an optical investigation of heat/mass transfer for vapor–gas mixture condensation and laminar film condensation in a vertical tube with gas present [4JJ–6JJ] also receive attention.

Unsteady-state influence

Here oscillation during steam condensation in subcooled water is examined analytically; the condensation of a single vapor bubble in subcooled water is considered; and the temperature in a channel cooled by a flow of a non-equilibrium vapor/droplet mixture is reported [7JJ, 9JJ, 10JJ]. The influence of periodic condenser movement on heat transfer is reported and the transient, condensing flow in a subcooled porous medium discussed [11JJ,12JJ,14JJ]. Vapor bubble collapse is studied in two papers [8JJ,13JJ].

Geometrical factors

Three papers report on the film condensation on vertical twisted tubes, the effect of channel orientation on the heat transfer with two-phase nitrogen flow, and condensation on a vertical sinusoidal fluted tube [15JJ–17JJ].

Surface and external effects

The presence of film surface waves for the flow along the top, inner surface of a horizontal pipe is reported [18JJ]. The effectiveness of a very thin coating of teflon in promoting the condensation of organic vapors is tested for 33 cases [19JJ]. Microgravity and its influence on condensation is considered in two papers [20JJ, 21JJ]. Condensation in annular two-phase flow of R113 is reported [22JJ] and the effect of condensate drainage on heat transfer described [23JJ]. Using tubes of various metals to which octadecylamine has been applied, the features of steam condensation are presented [24JJ]. Body forces during convective condensation on a smooth, vertical surface are examined and reported [25JJ].

Theory and analysis

A non-equilibrium theory for characterizing the surface deposition from particle-bearing condensable vapor flow is presented [26JJ]. Similarity analysis is used to describe condensing flow in a fluid-driven fracture [27JJ]. For condensation on a horizontal low-finned tube, a generalized prediction method for heat transfer is given, as is a model of film condensation for a bundle of such tubes, and the 'vapor-phase resistance method' applied to study condensation [28JJ–30JJ]. An evaluation of film condensation on horizontal integral-fin tubes is also reported [31JJ]. Other papers show the results of a numerical study of forced-convection filmwise condensation in a vertical tube, a closed form solution for average heat transfer during forced flow condensation on inclined surfaces and a non-linear stability analysis of forced flow condensation [32JJ–34JJ].

Experimental measurements

A number of papers report measurements on particular systems: downward flow of R113 vapor over bundles on horizontal smooth tubes; mixtures of R22 and R114 condensing inside a horizontal tube; ethylene glycol condensing on horizontal integral-fin tubes; horizontal tube condensation of mixtures of R113 and R11; and mixtures of R114 and R12 on horizontal finned tubes [35JJ–39JJ].

Laminar film condensation

This mode of heat transfer is studied on a vertical plate under transient conditions, inside a horizontal tube together with modes of flow, and surveyed from a fundamental viewpoint [40JJ–42JJ]. Yet another paper treats the influence of curvature on this phenomena [43JJ]. In a series of articles the modes and mechanism of transition between drop and filmwise condensation are treated [44JJ–46JJ].

Droplet condensation

In this regime, the behavior of a water drop on a rotating horizontal tube is reported, the heat and mass transfer to a spray droplet noted, and a theoretical study of the constriction resistance during this process set forth [47JJ–49JJ]. For propylene and ethylene glycols and glycerol vapor, drop to filmwise condensation on a copper surface with a monolayer promoter is described [50JJ, 51JJ]. Direct-contact condensation (opposed freon vapor jet in uniform water stream), characterization of droplet condensation from stagnant vapors as a function of a dimensionless number, and the application of a general equation for heat transfer to measurements on ethanediol complete the work in this area [52JJ–54JJ].

CHANGE OF PHASE — FREEZING AND MELTING

Phase change problems relevant to freezing and melting have long been a subject of widespread research in both academia and industry. Various interesting topics of research involved the classical Stefan problems;

solidification of alloys and metals including continuous casting processes; crystal growth; freezing and melting problems involving formation of frost, ice and snow; effects of thawing; high energy/laser applications; and ongoing investigations towards enhancing analytical and numerical methods for effective modeling/analysis. Various subcategories are identified below.

Stefan problems

Stefan problems have long been used as a basis for modeling and analysis of solidification phenomenon. Not much literature is available in this review other than issues relevant to numerical simulation of unidimensional multiple front problems and investigations of radiation–conduction heat transfer effects [1JM–2JM].

Solidification of alloys and metals and casting processes

Papers relevant to this subcategory focused both experimental and theoretical investigations. Those relevant to effects due to convection on such problems are summarized in a different subcategory. Experimental holographic measurements during alloy solidification appear in ref. [3JM] and measurements of solutal layers during unidirectional solidification appear in ref. [6JM]. Effects of surface solidification of steel ingots, planar flow casting of microcrystalline steel and growth of solid phase due to heat sink effects in a binary alloy appear in refs. [7JM–9JM]. Heat transfer effects during melting and solidification of metals, and related applications appear in refs. [5JM, 10JM, 11JM]. An investigation of continuous casting processes for a specific twin-roll type application is presented in ref. [4JM].

Solidification — crystals

Papers dealing with dendritic growth, directional solidification, magnetic field and hydrodynamic effects are described in refs. [12JM–20JM]. The physics and nature of crystal growth and influence of external effects seem to be the primary concern.

Freezing and melting : frost, ice and snow

There seemed to be quite some interest this year in investigations relevant to this subcategory [21JM–30JM]. Applications emphasizing frost-related problems included studies of formation and deposition in tube arrays, penetration and prediction of growth rates and frost layer buildups. Related studies involving ice and snow includes melting due to heating effects from surfaces, porous media, simulations involving various boundary conditions, etc. Other related studies involved energy storage systems, buoyancy induced flow effects, etc.

Freezing and melting : applications

Various related applications in this subcategory included theoretical, numerical, and experimental studies [31JM–51JM]. Theoretical investigations for freezing models involved parametric studies, characteristics of freezing heat transfer effects, supercooling, studies in freezing time calculations on simple geometric models, and applications to salt solutions and porous media [31JM–36JM]. Theoretical and experimental studies relevant to melting investigated processes of melting due to rolling contact, time-dependent boundary flux conditions, effects due to the presence of natural convection, energy storage systems, modeling of solid propellants, subcooling effects, contact heat transfer effects and heat transfer processes [37JM–51JM].

Thawing

Studies in this subcategory included theoretical and experimental investigations of thawing in soils and rocks. Other related papers included surface heat transfer effects due to forced convection, heat and moisture transfer considerations, and analytical approaches for heat conduction in the presence of freezing and thawing [52JM–56JM].

High energy heating/laser applications

Some interesting research studies of high energy heating effects and laser applications including pulse type boundary effects in freezing/melting appear in refs. [57JM–63JM]. Of the research studies in these areas, the applications included investigations of thermocapillary convection in cavities due to laser melting, multiple phase effects due to laser irradiation, substrate effects involving laser backscattering, laser welding applications, high energy beam penetration processes in melting flows, and pulsed heat source effects.

Effects due to convection

By far, effects due to convection seemed to be an important concern in various research investigations. Research topics encompassed both theoretical and experimental investigations. Amongst the various applications, effects of double diffusion convection due to melting, binary solidification issues involving convection, studies involving natural convection effects in freezing water, thermal convection effects in solid–liquid interface in alloys, buoyancy driven convective effects, and other related issues appear in refs. [64JM–76JM]. In addition, related applications involving convection are presented, in part, in the other subcategories.

Applications to mold/mold–metal interface studies

The effects of melting and freezing in solidification problems with application to mold and mold–metal interface has long been a subject matter of research interest [77JM–83JM]. A mathematical model for heat removal from a continuous casting mold is described in ref. [77JM]. Interfacial heat transfer and air gap studies between mold and metal are investigated in ref. [78JM]. Related investigations involve metal–mold heat transfer coefficients, mold cooling design problems, heat exchanges of melt and metal molds, and solidification analysis in a continuous casting mold.

Numerical simulations

With the advent of modern computers, numerical analysis methods have received widespread attention because of the several advantages. Various studies on the simulation of zone melting processes, binary solid–liquid phase change effects, convective–diffusion phase change with applications to melting of metals, three-dimensional solidification problems, and applications to liquid metals appear in refs. [84JM–88JM]. Reference [89JM] describes a new methodology of approach based on hybrid transfinite element formulations for applications to general heat conduction problems involving phase change.

Miscellaneous applications

Various studies involving melting and freezing applications appear in refs. [90JM–102JM]. These include studies on latent heat thermal energy storage in aqueous solutions and binary mixtures, latent heat approach for macro– micro modeling of eutectic solidification, thermal storage systems, and latent heat storage unit involving composites [91JM, 92JM, 95JM–97JM].

RADIATION IN PARTICIPATING MEDIA AND SURFACE RADIATION

One-dimensional studies in participating media

One-dimensional planar and axisymmetric cylindrical and spherical geometries are considered [1K–22K]. Some examples of the various numerical techniques used include the discrete ordinates method, spherical harmonics method, the zone method extended for linear anisotropic scattering media, and the Rosseland diffusion approximation. The papers deal with isotropic and anisotropic scattering problems, as well as methods for subtracting the diffraction scattering from highly anisotropic scattering problems. An extensive review of the engineering treatment of radiative transfer in participating media, and a review of engineering methods for computing the radiative heat transfer in power plants are included in this category.

Multi-dimensional and time-dependent radiative transfer studies

Two- and three-dimensional rectangular enclosures, and cylindrical and arbitrary media are studied [23K–40K]. Formulations of the exact integral equations and the solutions using discrete ordinates method, spherical harmonics method, continuous exchange factor method, Monte Carlo, and other numerical methods are included. Effects of real gases and the influence of refractive indices are also considered. The time-dependent studies in this category range from transient radiative cooling of droplets to time-dependent radiative transfer inverse problems.

Light scattering from particles and radiative transfer in particulate systems

Light scattering from spheres, spheres on conducting surfaces, cylinders, irregular inhomogeneous particles, and fly ash are among the works in this section [41K–57K]. Two flux parameters for fibers, coated silica fibers, and the Henyey–Greenstein approximation to scattering phase functions are also considered. Dusty media and ultra-fine powder insulations including their radiative transfer properties have also been studied. An overview of the existing knowledge on radiative transfer in packed and fluidized beds is included.

Radiation combined with conduction

Combined radiation and conduction problems are studied [58K–65K] for two-dimensional rectangular enclosures, gray planar medium, absorbing, emitting, isotropically scattering solid cylinder, absorbing–emitting medium, waste package canister, and semi-transparent material. The mushy zone in a phase change mode of semi-transparent material is also considered.

Radiation combined with convection

Several papers include the combined effects of radiation and convection [66K–76K]. Combined radiation and natural convection problem is considered for a vertical channel containing absorbing–emitting gas, and the stability of the fluids in a vertical cavity due to radiative effects are studied. Most of the papers deal with the problem of combined radiation and forced convection. Configurations considered are annular channel, gas pipe flow, diffuse gray tubular flow, circular pin, horizontal plate in a saturated porous medium, solid laden gas in a tube, laminar channel flow of non-gray gas, and unsteady planar flow with mirror boundaries.

Radiation in combustion systems

The effect of radiative transfer on fires in enclosures, large explosions, heat transfer enhancement due to non-gray features of radiative gases, flame structure and radiative properties in various diffusion flames are considered [77K–90K]. The combustion of aluminized composite solid propellent, and a cylindrical cloud of char/carbon particles are studied. The discrete transfer method, a coordinate transformation method, the flux type methods are used to analyze radiative transfer from flames.

Surface radiation

Several papers deal with surface radiation [91K–101K]. Seven papers report on shape factor results for a particular geometry, e.g. spherical segment to planar surfaces, or they consider calculation procedures for obtaining shape factors. Formulation of the enclosure energy analysis, and a generalization for open and closed enclosures with isothermal media are also discussed. Radiative transfer from fin arrays and roll-out fin expandable radiators are studied.

Radiative properties

Property inversion. Five papers [102K–106K] deal with the question of the inverse radiation problem of obtaining the radiative transfer properties such as the absorption coefficient, scattering phase function, scattering albedo, from measured reflectance, transmittance, or emittance data.

Engineering radiative properties

Absorption coefficient measurements, normal emittance measurements by transient temperature technique, transmission properties, reflectivity of refractory material are reported [107K–122K]. An ultrahigh vacuum system for measuring reflectance and transmittance, a vacuum emissivity meter, and a sample packing unit for diffuse reflectance infrared spectrometry are described. Emissivities for tantalum carbide, metal wires, thoriated tungsten, rhenium alloys, microgrooved silicon surfaces, porous spheres, coal particles, and nickel and titanium surfaces with various surface finishes, are presented. Emissive properties of solid–gas mixtures are also included.

Radiative properties of gases

Information on absorptance, broadened line widths, absolute intensity, and emissivity of various gases are presented [123K–138K]. These gases include methane, ethane, water vapor, carbon dioxide, and atmospheric gases. The Voigt line profile, and extension of band models to include scattering are also discussed.

Miscellaneous radiation studies

This section includes the papers [139K–157K] that deal with a variety of topics: interaction of radiative heat transfer with the atmosphere, ion-bombarded surfaces and laser induced plasmas, pulsed irradiation, phase change and heat transfer due to strong irradiation, blackbody radiation, radiative transfer in and through glass and other spectrally selective materials, multilayer insulations, infrared detectors, radiative transfer applications for space rockets.

NUMERICAL METHODS

In recent years, numerical methods have been used for a wide variety of applications. The papers that focus on the application of a numerical method for a specific problem are included in the category appropriate to that application. Papers that emphasize the details of a numerical method are reviewed in this section.

Review articles

Some reviews of the use of numerical techniques for heat transfer and fluid flow have been published [1N–3N]. These provide a framework for the understanding of the topic and give a large number of recent references.

Heat conduction

The heat conduction situation provides a convenient testing ground for the formulation and application of numerical techniques. Both direct and inverse heat conduction situations have been addressed in the methods described in refs. [4N–23N]. The methods described encompass one-, two-, and three-dimensional cases, steady and unsteady situations, and linear and nonlinear problems. The irregular geometries have been handled by the use of curvilinear coordinates or finite elements.

Phase change

The calculation of the solidification front or the two-phase boundary presents additional challenges to a numerical technique. Methods of dealing with the Stefan problem and other phase change problems are described in refs. [24N–28N].

Convection and diffusion

The numerical calculation of convective heat transfer requires the proper handling of the convection and diffusion terms in the energy equation. A similar treatment is also needed for the solution of the momentum equations. The convection–diffusion problems in the context of the finite-difference and finite-element methods are considered in refs. [29N–34N].

Flow equations

Extensive work has been reported on the development, modification, and application of numerical techniques for the calculation of fluid flow [35N–63N]. The work includes both forced and mixed convection; the formulations are generally based on the finite-difference and finite-element methods. Some of the important issues are: the use of staggered or non-staggered grids, the handling of pressure, multigrid or block-correction techniques, use of curvilinear coordinates, and underrelaxation.

Radiation

Special consideration to radiation heat transfer is given in the construction of numerical methods described in refs. [64N, 65N].

General techniques

Algorithms for the solution of general parabolic equations and for the implementation of the methods on parallel-processing machines have been described [66N–68N].

TRANSPORT PROPERTIES

The citations are arranged according to type of material: homogeneous solids, heterogeneous or porous media, and fluids.

Homogeneous solids

Topics of articles in this group include thermal conductivity measurements of vapor-deposited diamond and silicon, III–V compounds, superconductors, glasses, pseudoalloys, rhodium and Araldite [1P–8P].

Heterogeneous media

Thermal conductivity measurements as well as techniques for deducing conductivity from experimental data were reported for a variety of fibrous materials—such as fabrics and fiber-reinforced composites—insulation systems, disordered heterogeneous materials, soils and polymers [9P–18P].

Fluids

Transport properties of fluids were the focus of many articles [19P–29P]. Measurements of transport properties were reported for ammonia (gaseous and liquid), neon, methane, CF_4 and SF_6, and the current knowledge of the properties of steam was reviewed. Theoretical treatments were presented of the conductivities of reacting mixtures, polyatomic gases, heavy water, fluid metals, and liquid mixtures including crude oil fractions.

HEAT TRANSFER APPLICATIONS — HEAT PIPES AND HEAT EXCHANGERS

An impressive effort continues to be exerted in this area to apply basic heat transfer knowledge to the solution of practical problems.

Tube bundles

A number of investigations report on schemes used to promote heat transfer: static mixing elements for very viscous Newtonian fluids; grid-type turbulizers; helicoidal tubes; elliptical finned tubes; and highly finned tubes in staggered, equilateral, equivelocity configurations [1Q–5Q]. Related papers or notes consider particle embedment on in-line tubes in high speed gas flow, enhanced heat transfer by three-dimensional spiral ribs, temperature and stress fields in tube plates, and the flow and local heat transfer in staggered bundles of finned tubes [6Q–10Q].

Fins and various shapes

Attention is directed toward the heat flow and pressure drop behavior of flat tube and louvered plate fins, efficiency of helically fluted tubes, extended surfaces in pyrolysis coils, and two assessments of the thermal effectiveness of finned tube heat exchangers [11Q–15Q]. Other works treat perforated surface exchangers with passage variation, give an overview of plate and fin exchangers, study the influence of flow (two-phase) instability, and experimentally examine heat transfer from parallel louvered fins [16Q–20Q]. In a series of papers, natural-convective heat transfer results are given for vertical rectangular fins extending from horizontal rectangular bases [21Q–23Q]. The development of a high temperature plate-fin heat exchanger is given; the augmentation of a wavy type exchanger and the geometrical and thermal features of a spiral plate exchanger are described [24Q–26Q]. Heat transfer in finned systems, performance of vertical rectangular fins parallel to the main flow and the flow characteristics in tiers of parallel-plate surfaces are presented [27Q–29Q]. The enhancement of round tubes with wire turbulators, latent heat storage using finned tubes, the performance of direct expansion plate finned tube coils, and the flow losses for offset strip fins conclude the work in this area [30Q–33Q].

Heat exchangers

Those papers stressing design include: an alternate approach to multipass devices, investment costs and heat flow in stirred tanks, entropy and exchanger design, new heat flow and friction factor data for perforated plate units, the optimization of energy release in a radial device, key factors for steam generators heated by helium, shell and tube exchange design, exchanger design in the face of uncertainty in overall transfer coefficients, linear matrix operator formalism for basic design and impact of new technologies [34Q–44Q]. Additional design work treats: three-pass shell-and-tube, technical-economic optimization using anisotropic-porous materials, availability costs and optimum exchanger design, optimal synthesis of exchanger systems, and plate-type exchanger design for heat supply systems [45Q–51Q].

Where performance is the primary interest, there are a number of papers: heat flow and power needs in horizontal thin film scraped surface exchangers, experience and new system development of industrial units, low air side pressure loss in wind-tunnel exchangers, predicted and experimental shell-side pressure drop, schemes for improving the operating efficiency of exchangers, effectiveness of multipass plate units, and generalized solution for concentric tube devices [52Q–59Q].

Through analysis a number of findings result: a procedure for obtaining an explicit solution for the exit temperatures of the streams without iteration; a calculation of mean temperature difference for multi-tube pass cross-flow heat exchangers; a model of optimal tube circuiting in gas cooled cross-flow exchangers; an analytical (and experimental) study of a forced convection nocturnal radiator, effect of variable fluid heat capacities; effect of wound exchangers for air distributors; and countercurrent heat flow between parallel vessels with linear axial temperature gradient [60Q–66Q].

Fluidized beds are the focus of several studies: a pilot-scale vibrating exchanger for energy recovery from a hot gas, influence of bed variables on quenching operations, and a cooling tower using beds of various configurations [67Q–70Q].

The final group of papers treat a variety of topics: heat carrier interaction in a three stream device, units with grate dividing walls, comparisons of solar hot water systems at various collector and exchanger flow rates, a comparison of actual warming of air in the human airway with model behavior, and a review of flow maldistributions in exchangers [71Q–75Q]. Liquid–gas direct heat exchange, multipass exchangers with a single shell pass, and Stirling engine high-temperature heat exchange enhancement through radiation conclude this collection [76Q–78Q].

Recuperators

The contributions in this section may be grouped into more theoretical papers and those of a more applied nature. An approximate analysis is given for a regenerative exchanger, a regenerator in cyclic equilibrium with radiation is modeled, the flow and thermal effects in countercurrent water and air exchange is studied, and an overview of heat transfer in regenerators is presented [79Q–82Q]. The relationship between energy storage capsules and flow alignment is reported, the rapid calculation of the behavior of asymmetric counterflow regenerations described, and the thermal performance of exchangers applicable to waste-heat recovery systems given [83Q–85Q].

Addressing specific problems, the enameled heat exchanger for heat recovery applications is presented, a high-temperature exchanger for closed cycle MHD power generation studied, the utilization of boiler flue gas energy considered, the slab reheating furnace simulated, and the performance of shell-and-dimpled-tube heat exchangers for waste heat recovery given [86Q–90Q]. A high-temperature burner duct recuperator of advanced ceramic is evaluated, as is the design of rotary exchangers for gas turbines [91Q, 92Q]. Other papers with application emphasis consider non-metallic economizers, seal clearances in rotary heat exchangers, small sensible heat energy storage units, and the optimization of the precooler of a hydrogen fueled gas turbine [93Q–97Q]. Cogeneration heat pump system optimization, the modeling of a heat-pump energy storage system, and a design of a polytube ventilation air heat exchanger conclude this group [98Q–100Q].

Transient operation

This aspect of heat exchangers is considered from a variety of viewpoints: fin design when operating in longitudinal flow with transient heat flow, the influence of twist pitch in banks of twisted tubes on unsteady heat and mass exchange, the calculation of transients, and the dynamic characteristics of a counterflow plate exchanger [101Q–104Q]. The effect of uncertainties on the performance of a feed effluent exchanger, a theoretical and experimental study for unsteady temperatures, the transient response of rotary regenerators, and the unsteady flow and heat transfer in a plate-fin and tube exchanger further expand our understanding of this aspect of exchanger operation [105Q–108Q]. The study of transient temperature fields in cross-flow exchangers and fouling behavior of heat transfer surfaces under pulsating flow compliment the preceding papers [109Q, 110Q].

Evaporators

Design aspects include the experimental verification of a technique used for spray dryers, comparison of choices for evaporator cooler cores, use of a vibrating plate dryer for bulk materials, and the characteristics and process of heat transfer in a direct contact volume-type evaporation process [111Q–115Q]. A number of papers inquire into the evaporation mechanism: mist-cooling for heat exchangers, falling film heat flow analysis for a horizontal tube bank, the experimental determination of convective boiling coefficients in tubes of cross-flow compact units, and the analysis of two-phase flow instability in a vertical U-tube evaporator [116Q–119Q]. Related papers include the estimate of the internal heat transfer coefficient for a boiler drum, frost growth monitoring in evaporators, and performance test of a shell-and-plate type unit [120Q–122Q].

Condensers

Practical concerns motivate the papers in this section: analysis of the steam space in turbine condensers, performance test of a shell-and-plate unit, predicting performance of an evaporative condenser, evaluating and improving calculations for steam turbine condensers, and developing unified calculations for heat exchangers with condensation precipitation [123Q–127Q].

Fouling

Concern for this influence is directed to the effect of internal iron oxide deposits on temperatures in vapor generating tube of supercritical boilers, silica fouling of heat transfer equipment, the influence of thermal boundary conditions on calcium carbonate deposition in double pipe exchangers and an assessment of the mode of operation of clinker coolers and the effect on clinker properties [128Q–131Q].

Heat pipes

Both experiment and analysis mark contributions in this area. True void fractions of two-phase flow in the vertical annular channels of a loop are investigated; experiment and analysis are applied to a closed two-phase device with imposed convection boundary conditions; the heat flow analyzed in a two-phase natural circulation loop and in rotating heat pipes; and the critical heat flux at the operating limit of a closed two-phase unit observed [132Q–136Q]. For aligned tube rows heat-pipe exchanger performance is studied; the heat flow in an open thermosyphon observed; the heat-flow properties in screen-wick pipes presented; and the performance on an air-filled open tube with respect to wind direction reported [137Q–140Q]. A variety of pipe configurations attract interest: flat shape, corrugated tube, screen wick, bellows-type, parallel-walled and divergent-walled open types, and advanced industrial ceramic pipe recuperators [141Q–146Q]. Further studies seek to illuminate or augment the basic mechanism: a downward heat flow device using vapor pressure to pump liquid, experiments and analysis of convection in a double-loop thermosyphon, heat flow in an open rectangular unit, and heat flow for a closed two-phase thermosyphon [147Q–150Q]. A number of papers are concerned with specific applications or effects: the possible heat-pipe effects in the vicinity of buried high-level nuclear waste, or on foundations in cold regions, evaluation of heat pipes in avionic package cooling, low-temperature units as affected by long operation and non-condensable gas generation [151Q–154Q]. Other papers treat calculation problems for heat-pipe exchangers, the transient response of a liquid metal device, and material compatibility of sodium heat pipes [155Q–157Q]. A survey of high-temperature heat pipes and a field study of fouling influences complete the papers on this topic [158Q, 159Q].

HEAT TRANSFER APPLICATIONS — GENERAL

The category with the most papers in this area was laser processing. Carbon dioxide laser cutting [139S], comparison with resistive heating [128S], laser annealing [8S, 53S], and evaporative cutting [1S, 21S] demonstrate recent laser practices. Analytical studies of laser products involve steady state laser melting [15S], laser-assisted thermoplastic matrix composite tape consolidation [19S], unsteady high-power laser loop flow [83S], laser induced decomposition of silane jets [3S], structural changes of hypo-eutectoid steel in laser transformation hardening processes [61S], and comparisons between models of thermal fields in laser and electron beam surface processing [49S]. A finite-element model of heat flow in biological tissue undergoing laser irradiation [114S] introduces biomedical heat transfer as a popular category. Although the clinical applications of lasers are rapidly multiplying, it is still not clear how the laser exerts its effects. Relevant papers involve radial heat flow in skin [109S], combined macro- and micro-vascular model for whole limit heat transfer [116S], thermal modeling of the malignant woman's breast [92S], convective heat flux distribution over the entire skin surface of a male [94S, 95S], heat transfer during hyperthermia [28S, 131S], thermodynamic modeling during cell freezing [40S], the relation between the near field and local average tissue temperatures [146S], heat transfer in tissue radiated by a 432 MHz directional antenna [68S], and a mathematical model for temperature distribution of thermally processed shrimp [29S]. Other food related papers involve heat transfer in thin-film wiped-surface evaporation of model liquid foods [117S], heat transfer and friction coefficients for tomato puree [77S], drying [144S], and corn drying prediction models [127S].

A number of papers apply thermodynamic analysis to irreversible power plants [17S, 57S], supercritical helium [22S, 99S], simple hot air engines [91S], heat-transfer-based reconstruction of the concepts and laws of classical thermodynamics [16S], heat transformers [118S], and the analogy between thermal and electrical quantities [135S]. Other related papers involved journal bearings [65S], a spherical source with decaying power output [108S], liquid metals as heat transfer agents [50S], a high performance radiant heater with a porous medium energy converter [141S], radiation within internally partitioned regions [35S], and heat transfer in valves [147S].

Heat transfer in structures presents papers on non-stationary heat flow [33S], corners of external walls with non-isothermal surfaces [107S], new views on window heat transfer coefficients [20S], new design methods for heat loss from rooms [37S, 59S], pipe locations in trenches [10S], heat transfer to large objects in large pool fires [12S], and design factors in partially charged thermal storage tanks [4S].

Device related papers include fluidized bed thermal storage [45S], latent thermal energy storage capsules [58S], design charts for dynamic behavior of non-isothermal fixed-bed absorbers [93S], computer simulation of evaporative cooling towers [18S], extruder reactors [38S], tube reactors [101S], misinterpretations of diabatic regenerator performances [11S], and methods for predicting freezing design depth of dewatering sludge-freezing beds [76S].

Studies of local heat transfer coefficient including the combustion chamber walls of a 4-stroke gasoline engine [47S, 113S], and in diesel engines [48S, 111S, 112S, 136S, 137S, 145S], with swirl [100S], and diesel power stations [85S]. An increasing number of papers include electronic circuit boards and chips [9S, 26S, 54S, 60S]. Similar papers discuss predicting temperatures of stacked heat sinks with a shroud [97S], temperature prediction on substrates and integrated circuit chips [98S], single-chip pyroelectric detector array [134S], the effects of heat transfer process on the print quality in thermal printers [82S], toner fusing in electrophotography [80S], vapor phase soldering basics [56S, 105S], rapid solidification techniques on a cool substrate [75S], temperature distributions in the thermal wake of an IC package [138S], departure from natural convection in low-temperature boiling heat transfer encountered in cooling of microelectronic devices [90S], thermal and stress analysis of semiconductor wafers in a rapid thermal processing oven [74S], suppression of natural convection in a crystal growth reactor [25S], effects of spacing and length on convection from surface-mounted components [73S], and, finally, the cooling of future computer systems [52S].

Glass technology continues as an interesting heat transfer application [34S]. Reference [84S] gives calculations of the transient temperature distribution in glass formed in a metal mold. Other related papers involve radiation annealing of steel [96S], and centrifuge melt-spinning [14S]. Other fiber production papers describe thermoplastic filament winding [23S], calculation of heat exchange between yarns and heat-treatment contact surfaces [27S], numerical simulation of wire-coating polyethylene [81S], drying of latex backcoated acrylic fabrics [62S], and the use of metallic coatings to enhance thermal contact conductance [6S]. Finally several papers deal with fins; i.e. cooling fin performances for LSI packages [140S], a review of stagger~d pin fins for turbine cooling [7S], and automotive brake drums [39S].

A numerical analysis of fluid motion and heat transfer in a tank of a ship rolling in a wavy sea [2S] introduces interesting convection effects. Other related papers describe heat transfer studies on a rocket nozzle for naval application [36S], and calorimetric measurements of thermal control surfaces at geosynchronous orbit [5S]. A group of papers describing long-studied turbine problems such as temperature effects on particle dynamics and erosion in radial inflow turbines [121S], increasing the cooling efficiency using turbulizers [67S], and GASCAN — an interactive code for analyzing gas turbine systems [44S]. Emphasis on heat transfer processes during fabrication continues. Topics include computer modeling of non-autogenous welding [142S, 143S], pulsed current weld pool behavior [129S], the physics of fusion welding [71S], an arc welding heat source model [89S], effects of torch angle and shield gas [124S], and vibration welding of thermoplastics [119S]. Mathematical models of furnace behavior produced several papers. Analytical subjects discussed include: reverberatory furnaces [13S], diffusion furnaces [55S, 110S], tunnel kilns [41S], and heating furnaces [51S, 69S, 79S, 86S, 133S]. Other furnace papers give methods of monitoring heat losses [46S] and controlling radiant heat transfer [87S], predict temperatures in pulverized coal combustion [88S], and predict performance of natural gas fired units [115S]. Mold heat transfer is described for a number of metals and plastics [42S, 70S, 78S, 104S, 106S, 123S, 130S]. The design and performance of casting processes involves some 450 parameters [24S, 31S]. Continuous casting techniques [43S, 126S] also received attention. Numerical modeling of rolling [66S, 103S, 120S, 132S], grinding [72S, 102S], quenching [122S], gear tooth cooling [125S], and thermo-mechanical cracking [30S, 32S, 63S, 64S] add to the increasing literature of process and machining heat transfer.

SOLAR ENERGY

Regardless of the fact that solar energy research in the U.S. has waned since its heyday following the oil price shocks of the 1970s, solar energy is an area of vigorous worldwide activity. The papers cited in the bibliography include studies on flat-plate collectors, passive heating, active solar heating strategies, solar ponds, solar-driven absorption cycles, thermal storage, greenhouses, concentrating collectors, heat transport within systems, photovoltaic cells, and several other topics.

Flat-plate collectors

A dozen papers [1T–12T] provide analyses of the thermal performance of flat-plate solar collectors, which are well-suited to heating water for residential and commercial applications.

Passive solar heating

The Trombe wall and other passive heating techniques [13T–22T] offer low-cost methods for indoor heating.

Passive solar heating

The use of solar reflectors to heat air directly was examined in several papers [23T–27T].

Solar ponds

Solar ponds are thermal energy reservoirs. Salt-gradient ponds and alternatives to the use of salts were discussed in refs. [28T–32T].

Absorption cycles

Solar energy can be used as the heat source for driving the refrigerant out of solution in absorption refrigeration cycles [33T–37T].

Thermal storage

Thermal energy can be stored in water tanks, phase-change materials, fluidized beds, and solid walls [38T–46T].

Greenhouses

A long-established use of solar energy, the greenhouse, remains the subject of active research [47T–53T].

Concentrating collectors and materials processing applications

Concentrating parabolic and ellipsoidal collectors can be used for applications such as materials processing which require higher temperatures than could be provided by flat-plate collectors [54T–59T].

Heat transport within solar energy systems

Four papers focused on the use of heat pipes and other heat exchangers for transporting thermal energy from a solar collector [60T–63T].

Photovoltaics

Three of the cited papers concern heat transfer aspects of solar photovoltaic cells for electricity generation [64T–66T].

Miscellaneous solar energy heat transfer studies

A wide variety of solar energy applications are receiving attention. The list this year [67T–84T] includes desalination, air conditioning, ocean thermal energy conversion, a Rankine cycle power plant, Stirling engines, and domestic hot water. Additional papers discussed the use of molten salts, properties of solar insolation at various locations, software to optimize building energy use, and solar drying.

PLASMA TRANSFER AND MHD

The relatively large number of papers published in plasma heat transfer during the past year reflects on the continuing research activities in this field.

These activities may be classified according to the following subsections: electric arcs and r.f. plasmas, plasma processing, plasma diagnostics, theoretical investigations, and MHD studies.

It should be pointed out that the last subsection mainly contains papers which do not include plasmas as the electrically conducting medium.

In the following, the major research activities in each subsection will be summarized.

Electric arcs and r.f. plasmas

The majority of papers in this subsection [1U – 28U] are concerned with circuit breaker arcs and with arc welding. A number of basic studies refer to free-burning, high-intensity arcs.

Plasma processing

Studies in plasma processing [29U – 42U] range from fundamental studies of heat transfer from plasmas to particulates injected into the plasma, to plasma synthesis, plasma spraying, and plasma effects on flames.

Plasma diagnostics

The emphasis in plasma diagnostics [43U – 63U] has been on the employment of emission and absorption spectroscopy and probe measurements for determining governing plasma parameters. New developments should also be mentioned for measuring simultaneously size, temperature, and velocity of particulates injected into plasmas.

Theoretical studies

Most of the theoretical studies [64U – 71U] refer to calculations based on collisional-radiative models, to collisional rate coefficients, and to calculations of thermodynamic and transport properties.

MHD studies

Papers in this subsection [72U – 84U] are primarily concerned with natural convection in MHD, combined thermal and electric effects, two-phase flow phenomena, and non-equilibrium MHD problems.

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