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Heat transfer — a review of 1989 literature

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INTRODUCTION

THIS REVIEW surveys and characterizes papers comprising various fields of heat transfer that were published in the literature during 1989. It is intended to encompass the English language literature, including English translations of foreign language papers, and also includes many foreign language papers for which English abstracts are available. The literature search was inclusive, however, the great number of publications made selections in some of the review sections necessary.

Several conferences were devoted to heat transfer or included heat transfer topics in their sessions during 1989. They will be briefly discussed in chronological order in this section An international symposium on *Mathematical Modeling and Computer Simulation of Processes in Energy Systems* was organized by the International Centre for Heat and Mass Transfer and held in Sarajevo, Yugoslavia, 20–24 March It included papers on rewetting analyses, and numerical modeling of heat transfer in the development of new energy technologies. The proceedings are published by Hemisphere, Washington, DC. The *7th Eurotherm Seminar* organized by the Eurotherm Committee was held on 23–24 March in Rome, Italy, and was devoted to direct contact condensation, two-phase flow and boiling, measurement techniques, and transients and accidents. The *31st Heat Transfer and Fluid Mechanics Institute* sponsored by the School of Engineering and Computer Science, California State University, Sacramento, was held on 1–2 June It included papers on heat transfer characteristics of a thermally anti-iced aeroengine intake, heat transfer in an evacuated concentrating solar collector, in a pulse combustor boiler, in a micropolar fluid and in steel plant refractories. An *International Seminar on Fission Product Transport Processes in Reactor Accidents* organized by the International Centre for Heat and Mass Transfer, and held in Dubrovnik, Yugoslavia, 22–26 May, included a discussion of heat and mass transfer in the behavior of fission products The *1989 ASME Turbo Expo*, Toronto, Canada, 5–8 June, devoted seven sessions to heat transfer with rotation, internal and external heat transfer, augmentation, film cooling, transient, and unsteady condition. Inquiries about the presented papers should be directed to the ASME Order Department. The *7th Italian Congress on Heat Transfer* organized by the Italian Thermal Fluid Dynamics Society and held on 15–17 June, Florence, included in its program heat transfer in single and multiphase systems, in fission and fusion systems, in energy conversion and in air-ambient systems. The *6th International Conference on Numerical Methods for Thermal Problems* in Swansea, U.K., 3–7 July, included in its program computational aspects of heat transfer in composites and ceramics. The *26th National Heat Transfer Conference and Exhibition* was organized by the American Society of Mechanical Engineers and the American Institute of Chemical Engineers at Philadelphia, Pennsylvania on 6–9 August, and included seven panel discussions and eight plenary lectures in addition to the sessions and poster sessions dealing with all phases of heat transfer and its applications. More than half of the 395 papers were on two-phase flow. The 1989 Donald Q. Kern Award was presented to Abraham E. Dukler, who also presented the lecture on "Interfacial Waves on Thin Liquid Films: Mechanics and Transport". The 1988 Max Jakob Award was received by Yasuo Mori, who lectured on "Some Optimizing Examples in Forced Convective Heat Transfer". The *1989 ASME Cogen-Turbo III* sponsored by the International Gas Turbine Institute, Atlanta, Georgia, at Nice, France, on 30 August–1 September, was devoted to combined-cycle technology and cogeneration. It included lectures on short hole convection at high temperature and high Reynolds number and heat transfer in expanding parts. An *International Symposium on Heat and Mass Transfer in Building Material and Structure* was organized by the International Centre for Heat and Mass Transfer at Dubrovnik, Yugoslavia, 4–8 September. Proceedings of the conference are available from Hemisphere. An *International Conference on Fires in Buildings*, 25–26 September, at Toronto, Canada, brought together experts from the United States and Canada, as well as from European countries. Heat transfer aspects were included in the program. The *6h Hostile Environment and High Temperature Measurement Conference*, cosponsored by the Society for Experimental Mechanics and the

Technical Committee on Strain Gages, was held at Kansas City, Missouri, on 6–9 November. Many companies and research institutes participated in the discussion of instruments and measurement techniques in various applications The *10th Brazilian Congress of Mechanical Engineering* held on 5–8 December, at Rio de Janeiro, Brazil, included sessions on conduction, natural and forced convection, radiation, multiphase flows, phase change, mass transfer in porous media, and solar energy. The *110th ASME Winter Annual Meeting,* 10–15 December, at San Francisco, California, included the traditional program in heat transfer and its applications, among others, in gas turbines, aerodynamics, machining, superconducting materials and processing, in biotechnology, and hyperthermia E G. Cravalho, the speaker at the heat transfer dinner, discussed "Heat Transfer in Biology and Medicine — Past Success and Future Potential". The Heat Transfer Memorial Awards were presented to T. J Love, Jr. and R. J. Moffat The papers presented at the meeting are collected in special volumes available from the ASME Order Department The *9th Miami International Conference on Energy and Environment* presented by the Clean Energy Research Institute, University of Miami in cooperation with the International Association for Hydrogen Energy on 11–13 December, at Miami Beach, Florida, included heat transfer aspects in their various sessions organized according to applications. The proceedings of the *Second U.K. National Conference on Heat Transfer* held in 1988 at Glasgow, Scotland, are now available at the Sales Department, Mechanical Engineering Publications Limited, Suffolk, U.K.

A list of books related to heat transfer and new journals published during 1989 is presented on the following pages. To facilitate the use of the review, a listing of the subject items is made below in the order in which they appear in the text. The letter which appears adjacent to each subject heading is also added to the references cited in each category

Conduction, A
Channel flow, B
Boundary layer and external flows, C
Flow with separated regions, D
Heat transfer in porous media, DP
Experimental techniques and instrumentation, E
Natural convection — internal flows, F
Natural convection — external flows, FF
Convection from rotating surfaces, G
Combined heat and mass transfer, H
Change of phase — boiling, J
Change of phase — condensation, JJ
Change of phase — freezing and melting, JM
Radiation in participating media and surface radiation, K
Numerical methods, N
Transport properties, P
Heat transfer applications — heat pipes and heat exchangers, Q
Heat transfer applications — general, S
Solar energy, T
Plasma heat transfer and MHD, U.

CONDUCTION

Research relevant to the various aspects due to conduction heat transfer continues to progress at a steady pace. Various investigations and developments encompassing analytical/numerical and experimental studies have been attempted in 1989. Subcategories in the areas related to conduction include contact conduction/contact resistance, layered and composite media, laser/pulse heating effects and thermal wave propagation phenomenon; conduction in bodies and objects; conduction combined with convection; development of new approaches and algorithms, combined thermal–mechanical problems, inverse formulations and other miscellaneous application studies. Of special note is the increase in attention towards applications to electronics packaging and related areas

Contact conduction/contact resistance

Investigations in this subcategory have focused on theoretical and experimental issues towards providing a further understanding of contact phenomenon and contact resistance effects for a variety of situations Included are issues relevant to thermal constriction resistance, rolling contact heat transfer, modeling, sliding contact, applications to electronic packaging, and other miscellaneous studies [1A–10A].

Composites and layered media

The class of applications in this subcategory included heat conduction in anisotropic bodies, thermal properties of layered plate structures with source effects, and prediction of thermal conductivity, and temperatures in aligned fibrous composites [11A–14A]

Laser/pulse heating and thermal wave propagation

Laser applications and/or high energy localized heating aspects appear in refs. [18A–20A, 23A] and primarily deal with chemical vapor depositions, substrates, and temperature distributions in materials. Of continued research investigations have been non-classical heat conduction models which account for finite speeds of thermal energy transport [16A, 17A, 21A, 24A]. Other applications involving wave propagation appear in refs. [15A, 22A]

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

Conduction heat transfer issues in bodies and objects having repetitive or arbitrary geometries have primarily dealt with effective thermal conductivity formulations, closed form solutions, temperature fields in objects of simple geometries, and other analytical/numerical and experimental investigations [27A, 29A, 31A, 33A, 38A]. Other issues relevant to heat conduction in objects and bodies appear in refs. [25A, 26A, 28A, 30A, 32A, 34A–37A, 39A].

Conduction with convection

The relevant papers appearing in this subcategory appear in refs [40A–46A]. Investigations include characterization of blow-up for a semilinear heat equation with convection, conduction with forced convection, models for a four-stroke heat-barrier-piston engine, and analytical formulations of three-dimensional conduction with convective surfaces.

Methods, algorithms, and applications

Approximate methods and models both from analytical and computational viewpoints have been proposed for a variety of applications. General algorithms in conjunction with numerical simulations have been investigated for various heat conduction problems They appear in refs [47A–63A] Investigations included finite element, finite difference, and other approximation methods

Thermal–mechanical problems

A significant number of research investigations have been conducted in the area of interdisciplinary thermo-mechanical problems. Of interest lately has been the area of electronics packaging. Thermo-elastic/plastic effects also seem to be of quite some concern in most applications. Papers dealing with electronics packaging and other relevant applications appear in refs. [67A, 68A, 71A, 77A, 79A]. Papers dealing with general thermal–mechanical issues and applications appear in refs. [64A–66A, 69A, 70A, 72A–76A, 78A, 80A–92A]. Of special interest have also been thermal-stress wave propagation problems.

Inverse problems

While direct methods seem to be a natural concern, in certain instances, the need to formulate inverse models has been a subject of some research investigations. Typical papers in this area appear in refs. [93A–95A].

Miscellaneous conduction studies and special applications

Various studies and special applications dealing with conduction heat transfer have been attempted for a variety of situations. Since it is beyond the scope of this review to specifically identify individual contribution subcategories, readers are encouraged to see available references in refs [96A–119A]

CHANNEL FLOWS

Forced convection in straight-walled circular and rectangular ducts

The heat transfer of hydrodynamically fully-developed flow in straight-walled ducts continues to be an active research topic from both the theoretical and experimental perspectives. The flow of liquids and gases in long straight ducts is ubiquitous. The literature covers the spectrum from large industrial applications, such as the optimization of thermal insulation in oil-carrying pipelines, to the contemporary concerns of microchannel fluid flow and heat transfer relevant to the electronics industry and to the flow of blood in small arteries. These simple duct geometries also provide a convenient 'proving ground' for the validation of numerical schemes, most notably those having complicated turbulence models Several articles considered wall roughness in the turbulent calculations. Closed form solutions of laminar flow and approximate solution for turbulent flow are provided for circular and rectangular ducts having both symmetric and asymmetric thermal boundary conditions. The flow of supercritical water and nitrogen was also investigated [1B–17B]

Mixed convection

Buoyancy-enhanced and buoyancy-opposed flows were studied principally in vertical straight-walled ducts with isolated investigations of mixed convection in horizontal and sloped containers, cross-section geometries included circular, rectangular and annular regions [18B–26B]. These low Reynolds number flows were examined in both the laminar and transitional regimes, with some results reported for Reynolds numbers as large as $5x10^4$ in the presence of very high heat flux rates. Heat transfer rates were obtained in vertically heated ducts for upward and downward flow of liquids and gases The flow of supercritical carbon dioxide was studied experimentally as it passes up and down in a vertical tube. Reverse flow was reported in situations when the buoyancy forces were in approximate balance with the fluid inertial forces. Inflectional instabilities in the velocity field contributed to local enhancement of the heat transfer rates.

Irregular geometries

Straight-walled channels having annular, circular-sector and annular-sector cross-section were examined. Exact temperature and velocity fields were employed as initial conditions for one-dimensional flow in an annular tube. Perturbation methods enabled an approximation of the azimuthal temperature variations experienced in deformed annular ducts. One study found that a heated gas is less likely to relaminarize in an annular duct than under similar boundary conditions in a circular duct. Combinations of isothermal, constant heat flux and adiabatic boundary conditions were imposed parametrically on the straight and curved surfaces of circular- and annular-sectored pipes. Several studies considered the conditions necessary for heat transfer augmentation in channels with wavy/corrugated walls, a configuration commonly found in compact heat exchangers. The heat transfer characteristics of flow through narrow channel gaps were obtained to model the flow conditions experienced in rod-bundle arrangements. A unique annular duct was examined experimentally, where the inner wall was wavy and helical in nature. Other studies include a parabolic tube of circular cross-section and arrangements of multi-passage circular pipe [27B–43B].

Finned passages

The need for heat transfer augmentation in the cooling passages of turbine blades continues to motivate research in confined ducts with fins and protrusions, the corresponding pressure drop penalty was considered in most studies [44B–60B]. Rectangular and cylindrical fins dominated this area of the literature, although the work was approximately equally divided between numerical and experimental approaches. The rib angle-of-attack was carefully considered in rectangular channels of variable aspect ratio and flow visualization was employed together with heat transfer measurements to elucidate the mechanism responsible for enhanced heat transfer downstream of cylindrical protrusions. Various geometric arrangements of internal longitudinal fins were examined in rectangular channels; transverse fins placed on the external surface of a circular pipe were also studied

Secondary flow

The secondary motion of a fluid was established in rectangular, circular and annular cross-sectioned ducts by the centripetal acceleration encountered around corners, bends and in helically coiled channels. The placement of helical-tape elements within a duct was also used to generate a swirl flow superimposed on the longitudinal stream [61B–69B] Heat transfer rates can be enhanced under certain operating conditions although relaminarization and the reduction in heat transfer rates can also be experienced when compared to similar Reynolds number flow in ducts without secondary flow. The local heat transfer characteristics were documented experimentally on both the concave and convex surfaces of a helical flow in a rectangular channel. Under conditions of high curvature, the flow on the convex surface was observed to separate and form closed recirculation regions Three-dimensional effects were also measured. The axial variations in the local heat transfer rates downstream of a bend were documented for both fully-developed and sharp-edged flow entering the bend. One numerical study considered the flow structure and heat transfer in a recirculating region formed in a channel.

Oscillatory and transient flow

Periodically varying inlet temperature and pressure fields are common in pulse combustors and Stirling engines. Arbitrarily-shaped periodic inlet temperature profiles were examined experimentally in straight-walled and conical ducts. More controlled periodic temperature inlet conditions were imposed through numerical studies. The heat transfer rates in piston-driven flows were investigated for constant temperature and constant heat flux boundary conditions. The literature suggests that heat transfer rates depend on the frequency and amplitude of the imposed oscillatory motion as well as the shape of the temperature profile. Step changes in wall temperature were considered theoretically and transient heat loss through long insulated pipes was addressed experimentally [70B–80B].

Two-phase flow

Gas–liquid flow dominated this area of the literature, however there were selected investigations of gas–solid and liquid–solid flow [81B–96B]. The heat transfer and pressure drop characteristics were obtained in electrically heated vertical tubes of water, glycerine–water and silicone liquid with air as the gas phase. A description of the nucleation process giving rise to the growth of bubbles and droplets was also analyzed in ducts of varying geometry. A glass bead–water suspension was examined in a horizontal duct; heat transfer depended on the solid-volume fraction and the particle size. The transport of large solid bodies in water flowing through a duct was treated numerically. Heat transfer enhancement in gas–solid flows was considered theoretically in circular ducts and compared to experimental results in dusty flows. Heat transfer augmentation was found to be greater in gas–glass bead flows for smaller glass bead diameters.

Non-Newtonian flow

Non-Newtonian fluid flow and heat transfer was considered in the film lubrication of high pressure rollers; cavitation was included in the analysis. Fully developed polymer flow (polyacrylamide, polyethyleneoxide, and hydroxyethylcellulose) in rectangular channels was investigated experimentally, using constant temperature, constant heat flux and adiabatic wall boundary conditions. The non-isothermal flow of polymers into mold cavities of irregular geometry was simulated numerically. The developing heat transfer and fluid flow of a power-law fluid in the entrance region of an arbitrarily shaped duct was studied experimentally [97B–103B].

Miscellaneous

The heat transfer characteristics in the tip region of turbine blades were obtained by modeling the region as a narrow channel flow with a recirculation zone; numerical and experimental results were presented. The enhancement of heat transfer rates by the application of electrical and magnetic fields was investigated in straight-walled ducts Thermal field characteristics in a disk-drive storage system were modeled and compared to experimental measurements. Steady flow entrance regions were studied in circular ducts. Recycle in a turbulent duct flow was investigated. Helium II flow was examined in a variety of flow configurations and several rod-bundle arrangements were considered [104B–124B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Research in this area includes the following effects. unsteady and instability considerations, including transition; effects of external influences; effects of the fluid type or nature; flows with reactions or chemical or thermal non-equilibrium; compressibility effects; papers which focus on closure models, flow analysis or application of the second law; geometric effects and low-density effects.

Unsteady flows, instability and transition

Investigations of unsteadiness and instability include studies of laminar and turbulent flow instability, boundary layer transition, disturbances due to obstacles in the boundary layer or in the upstream flow, analysis techniques and unsteady jet configurations [1C–22C]. The laminar instability studies discuss standing versus traveling waves and effects of non-linear disturbances. Boundary layer transition papers cover effects of wall cooling, acoustic excitation or surface geometry and the influence of wakes from upstream obstacles such as airfoils or cylinders. Transition analyses include the energy flux theory and the coupled-map lattice model. Papers on flow unsteadiness include studies of peristaltic transport and unsteady heat transfer from a wire in longitudinal flow and from cylinders downstream of another perpendicular or parallel cylinder. Results of an analysis of jet flapping, observed with opposed plane jets, are shown.

Effects of external influences

Studies in this category include effects of vortices, free-stream turbulence, vibration, injection through the wall, surface nature such as a stretching sheet, surface effects such as conduction within the wall and thermal boundary condition effects [23C–48C]. The effects of nose-cone asymmetric vortices or longitudinal vortices generated inside and outside of the boundary layer or naturally occurring due to buoyancy are discussed. The effects of free-stream turbulence are shown for cylinders in cross flow including the stagnation line, turbine blades and convex-curved walls. The effect of severe injection at various angles through a porous wall is computed. Vibration effects are documented for spheres, discs, cylinders and a stretching sheet wall. Other stretching sheet studies include one with a micropolar fluid and another with a viscoelastic fluid. Conjugate heat transfer studies are presented for flow over a simulated computer chip, flow over a surface film such as a hot-film sensor and an impinging mist spray. Boundary condition effects are discussed for step changes or gradients in surface temperature.

Effects of the fluid type or nature

Special fluid behaviors are drag-reducing polymer solutions; viscoelastic, non-Newtonian and Darcian fluids; superfluid helium, aerosols; fluids containing energetic particles and fluids experiencing cavitation [49C–58C] The non-Newtonian fluid paper is for a wedge flow and the study of superfluid helium focuses on the super-normal interface. The aerosol paper discusses thermophoresis effects and the energetic particles are those trapped in the Earth's geomagnetic field.

Flows with reactions or chemical or thermal non-equilibrium

Papers in this category investigate either combustion or very high speed flows [59C–63C]. The effects on the growth of a shear layer due to heat released in a reaction are discussed and vapor-phase combustion on the surface of a meteor and chemical reaction on the surface of a blunt cone are computed. Large-eddy simulation is applied to a convective boundary layer with chemical reaction.

Compressibility effects

Most of the papers in this category deal with the effects of shocks on boundary layer flows [64C–78C]. The effects are: forced transition to turbulence, viscous heating, boundary layer separation and augmentation of airfoil heat transfer in gas turbines. Supersonic flows are studied for various body shapes and angles of attack (including three-dimensional effects) and on wavy and curved walls. One paper in this category is a presentation of measurements of unsteady heat flux in the compressible boundary layers within an internal combustion engine

Analysis and modeling

Studies in this subcategory are on turbulence models, coherent structures, microstructure and thermodynamic analysis [79C–84C]. A two-fluid model of turbulence is applied to boundary layers and jets and a Reynolds stress and heat-flux equation solution is coupled with a statistical model for triple products and applied to various flows. One paper analyzes heat transport by macroscale structures in free-shear flows and another uses the acoustic sounding technique to investigate the microstructure of planetary boundary layers. An expression for entropy generation in combined convective heat and mass transfer boundary layers is developed for optimizing specific applications.

Geometric effects

The various geometric effects investigated during the last year include ribs and fins, roughness features, baffles, disks, tube bundles, jet flows and falling films [85C–106C]. The rib and fin configurations include heat exchanger surfaces, ribbed plates, parallel channels and pipes, and finned plates. A prediction method for roughness is presented and the roughness effect of ice on heat transfer is discussed. A study with baffles includes their effects on the heat transfer from adjacent pipes. Other geometries include flow over a circular disk with the axis parallel to the flow, flow over tube bundles, plane gas jets and free-falling films

Low-density effects

Papers in this category include aerosol evaporation in a rarefied gas, analysis of the temperature jump, effects of a plate leading edge geometry and the nature of a rigid sphere gas [107C–110C].

FLOW WITH SEPARATED REGIONS

Regions of flow separation, recirculation and reattachment can be expected whenever a flow encounters a rapid change in geometry. Common configurations examined in the literature were the backward facing step, the forward facing step, and flow past isolated protrusions including cylinders, annular fins, and electronic components [1D–14D]. Studies of the separated flow past steps were concerned with the local heat transfer coefficients in the neighborhood of the reattached flow (backward facing step) or separation (forward facing step). The heat transfer rate at this critical position was found to be quite sensitive to the details of the flow in the 'buffer' region of the turbulent boundary layer. Hypersonic heat transfer and fluid flow was examined in the region behind a step, and for cross flow over a circular cylinder. Various tube bundles in cross flow were examined, having staggered and in-line arrangements. A unique study addressed the heat and momentum transport in flexible tube bundles. Limited research in jets and flames also appeared in the literature.

HEAT TRANSFER IN POROUS MEDIA

Porous media is broadly interpreted in this section as a mixture; a fluid phase (or phases) combined with a solid phase which has either interconnected pores or intergranular spaces through which the fluid may flow. Systems like these can have very large fluid–solid interfacial area in a small volume, serving to promote area-dependent physical and chemical processes.

Packed beds (forced convection)

Many applications employ packed beds in which the solid material, or bed, is fixed in place and the fluid is forced through it by an externally imposed pressure difference. Heat transfer between the phases, as well as heat transfer between the bed and its containment, have been studied and reported in several articles [1DP–12DP] including effects of unsteady operation, of exothermic and endothermic reactions, and of the flow of dust-laden gas.

Packed beds (natural and mixed convection)

The general topic of natural convection heat transfer is treated separately in Sections F and FF of this review, but those articles for which the main theme is the porous medium's influence are cited here. Several studies were reported of natural convection in porous media [13DP–22DP]. Most of these consisted of analytical or numerical models, each addressing a particular combination of geometry and boundary conditions. Two particular departures from the normal realm of Newtonian fluids influenced by a gravitational body force were a study modeling behavior of a visco-elastic fluid and another study involving a rotating porous medium. Experiments with natural convection's role in freezing of water in a porous medium were described. Three investigations of combined free and forced convection in porous media were reported [13DP, 18DP, 21DP].

Onset of natural convection and instability

Conditions necessary for the onset of natural convection in porous media were reported for several cases [23DP, 25DP, 27DP, 30DP] including experimental studies with the destratification of a pebble bed heat storage unit and with a water saturated layer with and without salinity gradients. Several analytical and numerical studies were focused on the instability of modes of natural convection in various geometries [24DP, 26DP, 28DP, 29DP] including a bottom-heated cubical domain, horizontal layers, and horizontal annuli.

Non-Darcy effects

The Darcy model, which treats the local mass flux of fluid as proportional to the local pressure gradient, is widely used in models of porous media. Departures from this assumption, acknowledging some combination of fluid inertial effects and solid boundary effects, were at the focus of many studies [31DP – 41DP]. Most of these investigations were analytical or combined analysis with numerical methods; one [39DP] provided new forced convection data with which the applicability of various models can be assessed.

Fluidized beds

When compared with fixed beds, fluidized beds have an additional mechanism of heat transport, the heat capacity of solid particles in motion. Models of fluidized bed heat transfer [43DP, 45DP, 53DP, 54DP, 57DP, 60DP, 62DP] were proposed and described for immersed objects (particularly horizontal tubes) and for freeboard (above the dense bed) surfaces. Experiments of, or related to, heat transfer in fluidized beds [42DP, 44DP, 47DP, 49DP–52DP, 56DP, 58DP, 59DP, 63DP–66DP] dealt with containing wall heat transfer, heat transfer and fluid mechanics near immersed objects (again, horizontal tubes in particular), freeboard heat transfer, the influence of particle size, and surface heat transfer in circulating fluidized beds. Analyses and experiments were also directed toward novel applications of fluidized beds [46DP, 48DP, 55DP, 61DP], respectively immersion cooling of electronic devices, food processing, thermal energy storage, and drying of biosynthesis products.

Combined heat and mass transfer in porous media

The general topic of combined heat and mass transfer is treated separately in Section H of this review, but those articles for which the primary feature is the porous medium's effect upon the process are cited here [67DP – 82DP]. Several models and experiments were presented [67DP, 68DP, 73DP, 75DP, 81DP] for combined heat and mass transfer in unsaturated porous media, chiefly water in soil. Models of phase change, most commonly in drying of porous materials, were also presented [69DP, 70DP, 72DP, 80DP]. Other combined heat and mass transfer efforts included models of porous adsorbents, evaporative cooling using a cellular packing, thermally induced soil consolidation, dissociation of hydrates in porous media, and heat and mass transfer in metal hydride beds

Other porous media studies

Many models and experiments regarding the effective thermal conductivity of porous media were reported [85DP, 88DP, 96DP, 98DP, 99DP]. Three papers described numerical investigations of unsteady doubly diffusive (magnetic and buoyant) convection in porous media [93DP – 95DP] A model for the propagation of phase change fronts in porous media [90DP] and a finite element method for predicting the evolution of such fronts [89DP] were described. Other studies included topics as diverse as the critical conditions for counterflow of superfluid and normal fluid He II in porous media, experiments with channel interaction in monolithic reactors, and the influence of air motion on the effective thermal resistance of insulation materials

EXPERIMENTAL TECHNIQUES AND INSTRUMENTATION

Heat transfer measurements

New methods and devices In studies of convective heat transfer from an isothermal surface, a new method is reported in which the surface temperature can be controlled even if the direction of the heat flux is reversed; the necessary energy transfer from the surface is provided by using the Peltier effect, e.g. junctions of dissimilar semiconductors [22E]. Liquid crystal coatings have been used to determine the heat transfer from a pin fin, both, in a transient way by mapping the temperature profiles, and with an isothermal surface [3E]. Another method for local heat transfer measurements from an isothermal surface for widely varying heat transfer coefficients makes use of the change of the wet bulb temperature under radiation heating conditions [17E]. The heat transfer between a hot gas and particulates has been measured by determining the change of the magnetic properties of the particles when their temperature approaches the Curie point [23E]. Periodically varying heat fluxes have been measured using a photoacoustic method for characterizing semiconductor devices and solar cells [26E] Use of a mobile heat source to study heat conduction in anisotropic media is described in ref [5E] New radiometer designs are discussed, for use in industrial high temperature furnaces [4E], or for avoiding condensation effects [13E] The extension of the frequency response of an IR detector is achieved by combination of a thermoelectric and a pyroelectric sensor [11E] New design features of calorimeters include a high pressure device for measuring mixing heats of liquified gases [12E], an adiabatic calorimeter for high accuracy calorimetry of metals with heater fine adjustment [16E], and a calorimetric flow sensor combining a thermal resistor and a temperature dependent resistor on pin shaped probe elements [25E]. A digital photogrammetric system for evaluations of Mach–Zehnder interferograms is described in ref. [19E], including software to deduce the heat transfer rate. A new method for measuring the heat transfer coefficient involves the transient heating of a thin metal ring placed over a fin of insulating material and comparing the ring temperature changes with the values obtained from a model [14E].

Accuracy improvement The influence of the transient response characteristics of various temperature measuring devices on the derived heat transfer values is discussed in refs. [1E, 6E, 10E], and an improved analysis involving the use of the time derivative of the thermocouple responses is offered [6E]. Measurement errors due to damping of oscillating heat fluxes in the substrate material are considered in ref. [20E], and radiation effects on fine wire responses are discussed in ref. [21E]. An analysis of systematic errors in radiometer measurements is presented in ref. [18E], while the effects of dynamic changes of bubble shapes on the results of hot film anemometers in two-phase flows are shown in ref [9E] Heat transfer measurement accuracy can be improved by using corrections for heat losses [24E], and by improving the wall temperature control [7E]. Lastly, the error introduced by radiative heat transfer from a heater strip for fluid heat transfer measurements is discussed in ref. [2E].

Cryogenic heat measurements. Measurement of phonon pulses using a cadmium sulfide thin film are reported in ref. [15E], and an algorithm for deconvolution of sensor frequency response and phonon capture pulse signal is presented in ref. [8E].

Temperature measurements

New developments The impact of microelectronic developments is seen in refs. [42E, 57E, 60E]. A CMOS microcircuit includes resistance thermometers and electronics and has been used for measurement of temperatures, flow velocities and vacua [42E]. Surface temperature measurement during thin film processing is achieved by a planar-insulated resistance thermometer [57E], and a silicon IC has been developed for measurement of temperature gradients in laminar and turbulent flows [60E].

Laser based techniques. A combination of CARS and LDV has been used to simultaneously measure temperature and velocity in reacting flows [40E]. Use of LIF for thermometry of a surface which has been prepared with a temperature sensitive phosphor is described in ref. [39E] Raman spectra from an Si microstructure allows derivation of the temperature by comparison with a theoretical profile [52E]. Temperature and density distribution have been determined using speckle photography and optical tomography in asymmetric flows [49E] and in flames [28E]. Flame temperature and density have also been measured using time resolved Rayleigh scattering techniques [30E].

Pyrometry. Accuracy improvements and adaptation to specific applications are reported. Error considerations include the wavelength error in two color pyrometry caused by the use of effective blackbody wavelengths [35E, 41E], and by the assumption of a gray body [34E], and it is concluded that single color pyrometry with a good guess for a value for the emissivity may be better than multi-wavelength pyrometry [34E]. Both techniques will have to consider that the measured light may be partially polarized and that there may be polarizing components in the optical system [54E] Pyrometers have been used for time resolved measurements of the shock temperature of chemically reacting powders [29E] and in coal combustion chambers [62E, 55E] Response time of optical fiber sensors in pyrometric applications is discussed in ref [44E].

Thermocouples and resistance thermometers Error analysis and accuracy improvement are the subject of refs. [32E, 43E, 46E, 51E, 63E]. Error causes discussed include variable fluid flow velocity [51E], position in flow stream [63E], and influence of bead size [46E], as well as the error in the measurement of the location in a solid body during conduction heat transfer measurements [32E] A combination of a thermocouple coated with a porous BN layer and an uncoated thermocouple has been developed as a miniature psychrometer for simultaneous measurements of temperature and humidity [36E]. A thermocouple based furnace calibration system with automated data acquisition is described in ref. [50E]. Accuracy improvements over a wide temperature range are obtained with a new electronic circuit for a Pt resistance thermometer [64E], and a similar objective has been pursued in ref. [31E] by the response time characterization, and by determining the reproducibility [59E] of commercially available thermometers Calibration of a carbon-glass thermometer is presented in ref [38E].

Miscellaneous measurement techniques. Improved accuracy for a liquid crystal thermometer has been achieved by replacing human sensing with a spectral sensor and digital image processing [27E], and silicon diode sensor accuracy has been improved through a new digital circuit [47E] The use of a silicon diode thermometer as a sensor in thermoelectric power generation equipment is described in ref. [53E] Thermal imaging based on radiation detectors is improved through the use of new image processing algorithms [33E] An acoustic temperature measuring technique involving sound velocity measurements in acoustic waveguides has been applied to the determination of temperature profiles in large furnaces [61E] Temperature fluctuations have been determined with a double hot wire probe up to moderate turbulence intensities [48E]

Cryogenic temperature measurements Extensions of the measurement range have been reported for a constant volume gas thermometer by using He3 [58E], and for carbon and germanium resistors [56E] New electronic circuitry has led to improved responses [37E, 45E] of resistance thermometers at ultralow temperatures

Specific applications. Thermometry of flames is discussed in refs [28E, 30E, 40E, 46E], combustion in furnaces is dealt with in refs [29E, 50E, 55E, 61E, 62E], microelectronic applications appear in refs [52E, 57E]. and temperature measurements relevant to heat exchangers or condensers are described in refs [43E, 51E, 63E]

Velocity measurements

New developments. The heat loss from a surface acoustic wave (SAW) oscillator chip results in a temperature change of this device, and hence a change of its characteristic frequency; the measurement of this frequency change has been used to measure flow velocities causing the heat loss [81E]. A fluidic flowmeter has been developed that traps some of the fluid in vortices and measures the pressure fluctuations generated by these vortices, the pressure signal frequency is proportional to the flow velocity [87E]. A miniature five hole pressure probe allows the measurement of the mean of the three velocity components in laminar flows [85E]. An acoustic Doppler velocimeter has been designed for non-intrusive measurements of pipe flow velocities, measuring the phase angle between ultrasonic signals across the pipe with and without flow [80E].

Hot wire anemometers Methods for improving the accuracy or reducing the errors dominate [67E, 72E, 74E, 75E, 93E, 95E] The improvements include a new analysis for reducing the error in directionality [95E], considerations of effects of too small length/diameter ratios [93E], improved calibration procedures by the use of a polynomial description of the flow velocity [75E], and a dynamic calibration procedure using a sinusoidally varying velocity [72E] True time averages of velocity components have been obtained by measuring the velocity reversal using a combination of two X array probes [67E], and a single wire probe has been used for the determination of the fluctuation of the axial velocity component in non-isothermal flows [74E]. Accuracy improvements using new arrangements of three wire probes include a combination of a X array hot wire with a cold wire to correct for yaw angle and temperature effects [65E], three single wires in one plane for measuring the three velocity components [68E], and a pulsed hot wire between two resistance thermometer wires serving as flow sensors in two directions [78E]. Several arrangements have been developed in a subminiature format, i e 0 6 μm wire diameter and 200 μm wire length [86E].

Laser velocimetry. Corrections for finite beam dimensions have been obtained with two beam focus velocimetry with a newly developed algorithm [84E], and corrections for the non-planar nature of the wavefront of light reflected from a cylindrically expanding fluid are presented in ref [77E]. Measurement of two-dimensional velocity fields using laser speckle velocimetry for unsteady flow has been improved by periodic irradiation of the fluid with a sweeping beam of a cw laser instead of a pulsed light source [83E]. Additional laser flow measurements are discussed in the multi-phase flow section

Multi-phase flows. The velocity and the size of particulates or bubbles have been measured using two slightly displaced, crossed laser beams [82E]. Holography together with small angle light scattering has been used to characterize two-phase flows including droplet size [66E] Optical sizing of bubbles diverted into a capillary with two detectors is described in ref [91E]. Hydrogen bubble flow visualization has been improved by new electronics for the pulsing of the bubble forming wire and the detector synchronization [69E]. A new method for flow velocity measurements of dense suspensions involves the charging of the particulates with a corona discharge and a downstream electrostatic probe for charge detection [92E] A combination of velocity determinations using charge transport measurements, and of solid concentrations using capacitance measurements allowed the determination of mass flows of solid material in flowing suspensions [94E]. Hot film anemometry has been used to determine the particle motion in hydro-acoustic fields, with the film response being proportional to the particle displacement [71E]. An improved photodetection system for a laser Rayleigh scattering apparatus has been used for droplet concentration measurements in expanding fuel jets [70E], and a particle size measurement technique for dense suspensions has been developed making use of backscattering measurements using a bifurcated light fiber assembly [79E].

Miscellaneous flow measurements. The deflection of a quartz fiber anemometer has been used for determination of the average velocity in air ducts without the need of traversing the duct [73E]. A double spark Schlieren system has been developed for the visualization of supersonic flows [89E]. Free convection flows in porous media have been measured using fluorescent dye and an array of multiple fiber optics fluorescence probes incorporating excitation signal transmitter and fluorescence sensor [90E]. The use of electrochemical probes for velocity measurements is described in ref. [76E] for visco-elastic flows, and in ref. [88E] for pipe flows.

Concentration measurements. A planar LIF system has been developed for the measurement of OH radical densities and of local temperatures in diffusion flames for investigation of the large scale structures in the shear layers [96E]. A dual wavelength thermal lens spectrometer offers trace element analysis in a two component mixture with very high sensitivity [98E], and a theory for thermal spectroscopy is presented predicting thermal response characteristics for various reaction kinetics [97E].

Property measurements

Thermal diffusivity. Variants of the pulse heating method are presented in refs [106E, 110E, 111E, 114E], including laser heating of a thin film or a foil and a temperature change measurement on the backside [111E], the heating for a finite pulse length of the centerline of a cylindrical rock sample at high pressures [114E], and the heating of ruby and of PMMA with a pulsed planar heat source [110E]. Measurement of temperature distributions yields simultaneously values for the thermal conductivity. Light induced spatially periodic temperature distributions in diamond allow the derivation of the thermal diffusivity values from diffraction of a cw laser beam [106E]

Thermal conductivity. Improved measurements for thermal conductivities include new curve fits for alumina [113E], a dynamic method for biomaterials involving heat pulse exposure and temperature decay measurements [100E], temperature distribution measurements in porous media heated by chemical reactions after a burst of one of the reagents [105E], and the measurement on powder metallurgical samples of different densities using a comparison method [99E]. Transient wire heating at high pressures has been used for measurements on liquids near the critical state [107E], and the effects of a microgravity environment for thermal property measurements on metal alloys has been investigated in ref. [112E]. New electronics for providing accurate heating pulses [104E], and a new apparatus for thermal property measurements at ultra high pressures (e.g. for the determination of the phase behavior of liquid crystals) are described in ref. [102E].

Other properties. A new method for simultaneous measurements of viscosity and density has been developed using measurements of the propagation of a torsional stress wave along two differently sized waveguides submerged in the liquid under investigation [109E] Methods are described for the measurement of thermal expansion coefficients of thin films using an optical measurement of the substrate warp [108E], and of solid bodies using a computer analysis of the fringe shift of an interferometric measurement [115E]. The problem of measuring the temperature dependence of total emissivities is discussed in ref. [101E] and an algorithm and procedures are developed for optimization of the experimental conditions. More accurate results for the measurement of an optical Kerr effect can be obtained when a cw laser is used rather than a pulsed laser, and when corrections for thermal heating are employed [103E].

Miscellaneous new instrumentation. The accuracy improvement of pressure or vacuum measurements are discussed in and corrections offered for capillary effects in small bore manometers [118E], and for thermoresistor vacuum gauges [116E]. An improved error analysis method involving line regression with two variables subjected to errors is presented in ref. [119E], and a new processing technique for experimental data by means of asymptotic variables instead of dimensionless variables is suggested in ref. [120E]. A new method for measuring irregularly shaped, three-dimensional bodies using raster stereography is described in ref. [117E]

NATURAL CONVECTION — INTERNAL FLOW

Horizontal layers heated from below

Convection in horizontal fluid layers heated from below remains an area rich in problems and often provides understanding of the evolution of flows from simple to complex forms It has proven an area of great interest not only to the engineer, but also to the applied mathematician interested in non-linear phenomena and to those who use fluid mechanics in a variety of fields of the basic and applied sciences

Onset of flows and instabilities. A number of papers [1F–15F], using numerical, analytical, or experimental approaches examine instabilities and transitions in Rayleigh–Bénard convection. Some consider the first instability, the onset of flow, in a layer as dependent on the aspect ratio, multi-component fluids, and a fluid with an inversion in its density as a function of temperature At higher Rayleigh number the instabilities and transitions, and the resulting convection patterns have been examined over a range of Rayleigh number and Prandtl number including the possibility of bifurcations, and the influence of sidewall conductivity. Some of these consider the flow structure and resulting velocity patterns and heat transfer that are present in the layer. Other studies consider the influence of thermally anisotropic walls on the planform of the convective flow, a shadowgraph method for analyzing low Rayleigh number convection in liquid crystals, and the use of pseudo-spectral simulations of the flow and instabilities over a range of Prandtl number.

High Rayleigh number convection Several studies [16F–22F] consider high Rayleigh number convection where there is potential onset to turbulent flow These works include consideration of, what has been called by one group, hard and soft turbulence, as well as analyses of asymptotes for large Rayleigh number and infinite Prandtl number flows, and the possibility of large scale vortical structures. Other studies consider the influence of coherent structures in a relatively chaotic flow as well as the complex convection in a fluid which has a density maximum as a function of temperature and high Rayleigh number flow in silicone fluid

Miscellaneous studies in horizontal layers A number of other studies on convection in horizontal layers have been described [23F–33F]. Several consider unsteady natural convection in horizontal layers, including the influence of an arbitrary cross-section and flow in prismatic shaped enclosures. Studies also have been done on the influence of a combined vapor and non-condensing gas flow in a horizontal layer, and the influence of turbulent motion on magnetic fields Layers with internal energy sources have been considered as has the onset of flow with high frequency vibration and the influence of rotation. An analysis indicates the onset of oscillatory interfacial instability Experimental studies have been reported on convection in layers including air superimposed over water, in two immiscible liquids as well as fluids over a porous layer of a different fluid Several of these studies provide flow visualization as well as information on the heat transfer

Double-diffusive flows

The density variation driving convection may be due to differences in concentration, as well as differences in temperature Such mass transfer driven flows follow similar laws to heat transfer driven flows, though the diffusive constants are usually quite different In a number of situations, the density variation across a fluid is due to variations in both concentration and temperature, giving rise to what is commonly called double-diffusive convection Recent studies [34F–40F] include non-linear dynamics in such flows, the influence of traveling waves near the onset of flow, and the effect of partially permeable boundaries. Other studies report on instabilities in a triply diffusive system where three components are diffusing, a convenient system for setting up a double-diffusion apparatus with controlled initial conditions, and a simple model of chaotic motion with and without noise present.

Marangoni convection

Convection in horizontal layers can be driven by variations in the surface tension or surface free energy across an open or free horizontal bounding surface of a liquid. Such flows are called thermocapillary flows or Marangoni flows; they occur in thin layers of fluid, sometimes with an overlapping Bénard flow due to density differences across the layer. Many problems related to thermocapillary flows occur in manufacturing, in which melting takes place, or in crystal growth. Recent studies [41F–51F] include a linear stability analysis for a fluid with a freely deformable surface. Other studies consider fluids with localized heating or cooling of the horizontal surface, in laser processing of materials, in a floating zone under normal or micro-gravity, and in an open boat or a container of finite dimensions. Convection in a thin layer of evaporating liquid and the evaporation of a drop of fluid on a plane free surface have also been described.

Inclined layers

Buoyancy-driven flows in inclined slots [52F–56F] include the effect of variable viscosity fluids, a numerical study for different aspect ratios, inclined ducts, and local measurements in an inclined air layer. Related studies include convection in an inclined enclosure with a partition and in a trapezoidal cavity which is heated non-uniformly on its lower surface.

Differentially heated layers and vertical ducts

A number of studies [57F–88F] consider the flow and heat transfer in differentially heated layers which are heated from one (usually vertical) wall and cooled on the opposite wall. Research includes theoretical and numerical work covering the instabilities occurring in such flows, numerical work on oscillatory flow, analysis of convection rolls in a shallow cavity, a description of three-dimensional laminar flow in an air layer, a semi-empirical analysis which includes a turbulent thermal diffusivity, and an analysis of the transient flow when a cavity is suddenly heated. Experimental works include measurement of flow in an open cavity, of the turbulent transport in a cavity containing air, and of the influence of multiple partitions in a cavity. Combined moisture and heat transport, and additional temperature variations on the upper and lower bounding surface have also been considered. Measurements of the three-dimensional structures and the heat transfer in water near its maximum density point of 4°C have been described

Horizontal circular tubes, annuli and spherical shells

Research on convection in horizontal circular tubes, annuli and spherical shells include a number of numerical and experimental studies [89F–105F] These include numerical studies on unsteady convection in horizontal annuli and non-steady three-dimensional flow in a horizontal cylinder of compressed gas, as well as an analysis of convection in eccentric annuli over a large range of Knudsen number Special models that have been used included consideration of temporal and spacial transitions in such flows in horizontal annuli, and use of a pressure gradient method for studying transient convection in a horizontal cylinder and in a spherical shell A pseudo-spectral method has been applied to high Rayleigh number convection and a different model to the flow in a closed spherical container. Experiments on the flow in an annulus include application of an interferometer to examine the density field in an eccentric annulus, measurements in low temperature helium, the use of liquid crystals for visualization of the temperature and flow pattern, and measurements of the unsteady three-dimensional behavior in a combined air–water layer in a horizontal cooled circular tube where water is near its maximum density point. Experiments of convection in a hemisphere give the heat transfer over a wide range of Rayleigh numbers.

Thermosyphons

Thermosyphons [106F–108F] are natural convection flow loops where one side of the loop is at a higher density than the other side. They are widely used in solar energy and other systems where they provide self-regulated flow and avoid the necessity of pumps. The heat transfer in two-phase thermosyphons in which the flow channel is the outer annulus and the inner cylinder of vertical concentric cylinders and in single phase flow in a simple channel have been studied. Dynamic behavior and chaotic flow have also been reported

Porous media

Buoyancy-driven flow in porous media is covered partly in this section and partly in Section DP of this review which specifically covers flow in porous systems Recent studies [109F–112F] consider special models for natural convection in a differentially heated shallow porous cavity and the onset of convection in a horizontally unbounded saturated porous layer heated non-uniformly from below. General characteristics of the flow in a shallow layer indicate a strong core flow over a wide range of parameters.

Mixed convection

Although much of the recent work done on mixed convection in internal flows is cited in the present section [113F–137F], there are some related works described in Section B on channel flows. The work includes studies on mixed convection with combined natural and forced flows in vertical ducts, horizontal ducts, inclined ducts and miscellaneous shaped chambers. Work on mixed convection in vertical ducts includes a stability analysis of convection in an annulus of large aspect ratio, an analysis of convection in narrow vertical ducts, and studies of the influence of a recirculating flow in a vertical pipe, as well as the influence of mass diffusion on such flows. Other studies provide empirical correlations for the heat transport in laminar flow and experimental results on transitions to turbulence. Studies of convection in horizontal tubes and ducts include the influence of small cross flows on Bénard cells, the effect of wall thermal conduction, and an analysis of flow in an asymmetrically heated channel, and one for convection in a saturated porous annulus. Analyses of mixed convection in inclined layers includes the upward and downward flow in the entrance region between inclined parallel plates and flow reversal in opposed convection in inclined pipes Other studies consider mixed convection flows in rectangular cavities, in a cavity with a moving upper surface, in branches of piping, and through small openings in a partition

Miscellaneous studies

A number of other geometries and flow conditions have been considered [138F–152F]. These include convection in square cavities with partially active walls, the influence of variable properties in cavities with partially heated bottom and side walls, the influence of baffles in cavities for time varying convection, and flow in a container as it approaches a uniform state. Still others consider the effects of magnetic fields on convection in enclosures, transient heat transfer in helium II, and flow in partially open cavities.

Applications

Some specific applications examined [153F–159F] include flow in the melt during the growing of single crystals, using the well-known Czochralski technique, convection in a simulated liquid metal cooled nuclear reactor and flow in super critical helium in a conduit, as well as convection in a stairwell and in the early stages of a fire before flashover occurs.

NATURAL CONVECTION — EXTERNAL FLOWS

Natural convection in external flows has been extensively studied. The work includes both theoretical and experimental studies and pertains to many geometries. Two common geometrical configurations are vertical surfaces and horizontal surfaces. Whereas most investigations deal with laminar flows, some studies have focused on the measurement and/or computation of turbulent flows.

Vertical surfaces

Natural convection on vertical plates, rods, cylinders, and similar surfaces has been investigated in refs. [1FF–40FF] The studies are mostly concerned with steady flow, although some work has been reported on unsteady or oscillatory flows. The effects of simultaneous heat and mass transfer (or double diffusion), mixed convection, suction or injection, and stratification have been taken into account Some papers deal with moving plates or surfaces Also, plates with ribs and wavy surfaces have been considered. Natural convection has been studied for, in addition to Newtonian fluids, micropolar fluids and non-Newtonian flows.

Horizontal surfaces

Natural convection from horizontal plates and wires has been considered in refs [41FF–52FF] The studies include steady and unsteady flows The Bénard problem is investigated in a number of papers Natural convection in micropolar fluids and porous materials has been studied.

Turbulence

At large Rayleigh numbers, the natural convection boundary layer becomes turbulent. Detailed experimental studies and computational predictions for turbulent natural convection have been reported in refs. [53FF–59FF] The predictions include the use of two-equation turbulence models and the coherent structures derived from large-eddy simulations.

Other studies

Natural convection in more complex geometries and physical conditions has been considered in refs [60FF–79FF] The geometrical complications include inclined surfaces, fins or fin arrays, obstacles, rectangular corners, and three-dimensional bodies of arbitrary shape. Mixed convection in a plume and the behavior of a buoyant wall jet have been considered The effect of sudden heating has been studied

CONVECTION FROM ROTATING SURFACES

A small number of theoretical investigations (and a smaller number of experimental studies) involving rotating surfaces were reported

Rotating disks

Flow and heat transfer effected by rotating disks were studied [1G–6G] via experimental measurements and theoretical calculations. The situations explored contained combinations of stationary and rotating disks, three of the six papers focused on the behavior of disk drives, only one of which included physical experimentation.

Rotating channels

Experiments and analysis [7G] suggested an enhancement of heat transfer due to the Coriolis acceleration in a rectangular-section coolant channel rotating about an axis perpendicular to the channel, as in a cooled turbine blade A series of four papers [8G–11G] described analysis of heat transfer in flows in axially rotating pipes the rotation of which enhanced laminar flow heat transfer and impeded heat transfer in turbulent flows

Other flows with rotating surfaces

Heat transfer was also explored within an annulus with a rotating center cylinder [12G], in rotating cavities [13G, 17G], in external flows over rotating bodies [14G, 15G, 18G], and in boiling of cryogenic fluids [16G]

COMBINED HEAT AND MASS TRANSFER

Papers reviewed under this category fall into a number of somewhat disparate areas. One general subject concerns convective heat transfer at a surface through which mass flows, including transpiration cooling, ablation, and film cooling A second area relates to jet impingement flows and heat transfer with wall jets. Other areas relate to mist or spray cooling with liquid droplets impinging on a surface, to drying systems, and to general convective transport with simultaneous mass and heat transfer.

Transpiration and ablation

With transpiration, in addition to a convective flow over a surface, there is a net mass flow through a permeable surface. This mass flow through the surface may be positive (blowing) into the region where the main convective flow is or it may be negative (suction) Generally, transpiration is used with a positive flow to protect a surface from a chemically active main flow or, more often, a high temperature environment. Studies on transpiration related heat transfer [1H–5H] include systems with uniform suction and/or blowing through simple surfaces and also the influence of a non-uniform blowing and suction, localized blowing on curved surfaces, mixed convection and flow through a sheet the area of which is increasing from stretching. Reports on ablation include the influence of time varying heat flux and highly localized heating from a laser beam [6H–7H]

Film cooling

Film cooling [8H–18H] in which a gas is introduced at a discrete location or locations on the surface over which a high temperature fluid flows can lower the temperature in the boundary layer and thus the wall temperature itself. In gas turbine systems film cooling is often used in the high temperature stages of the turbine both for the fixed and rotating blades. Studies have concerned the influence of surface curvature, full surface film cooling, approaching thermal boundary, and the optimization of the cooling processes for gas turbine systems. In addition, measurements with jets in a cross flow have been used to improve understanding of film cooling Mass transfer systems with foreign gas injection have been used to simulate the heat transfer phenomena in various injection geometries. The general mixing of heated turbulent jets in a cross flow which occur with high injection rates was also considered.

Jet impingement heat transfer

Submerged jets Impinging jets can provide high localized heat transfer because of the very thin boundary layers present near the center of the impingement region. For this reason, they have found a wide application in providing high rates of heat and mass transfer A number of studies [19H–28H] considered heat transfer from submerged jets in which the fluid in the jet is the same as that in the ambient through which the jet flows to the heat transfer plate The influence of jet geometry including slot jets, single circular jets, arrays of circular jets and annular jets, in some cases with a cross flow, have been studied Some of these works consider the overall heat transfer, others the velocity and temperature distribution to improve understanding of the flow field and transport mechanisms. Jet impingement in compartment fires has also been studied.

Free jets. In a free jet, the jet fluid is different from that of the surrounding ambient. Often the jet is liquid and the ambient fluid a gas, perhaps air The heat transfer with liquid jets [29H–33H] impinging on solid surfaces has been studied including the influence of wall thermal boundary conditions, jet geometry, as well as the use of two-phase jets Because of the generally large difference in the viscosities and densities of the jet and ambient fluids, the flow field is quite different than in submerged jets as is the heat transfer distribution.

Spray and mist cooling

Related to liquid jet impingement is spray cooling in which a spray of liquid droplets impinges on a surface [34H–35H]. In the resulting thin boundary layer, evaporation can provide very high heat transfer Such systems have been used in casting and other processes

Drying systems

One field in which heat transfer and mass transfer are closely linked and interdependent is drying. Recent work [36H–45H] describes a number of systems for drying particles in fluidized beds and spray systems, more classical evaporative dryers, dehumidifiers and even such applications as drying cut grass. Many of these systems are closely linked to industrial applications.

Miscellaneous

Other papers cover a variety of processes with combined heat and mass transfer [46H–51H]. These include problems with combustion in cellulosic materials, thermal diffusive effects in moisture transfer in the ground, small Knudsen number flows, as well as some analyses of equilibrium and anisotropic processes.

CHANGE OF PHASE — BOILING

In recent years thermal transport phenomena, associated with liquid-to-vapor phase change, have emerged as primary areas for research, modeling/simulation, and system development. The application of evaporative cooling and boiling heat transfer to electronic systems has brought new excitement to a field traditionally focused on steam generators (fossil fuel and nuclear) and refrigerators (conventional and cryogenic). The archival heat transfer literature in 1989 reflects substantial activity in boiling incipience, vapor bubble characteristics, nucleate boiling, critical heat flux, film boiling, boiling from porous surfaces and in porous beds, enhancement of ebullient heat transfer, boiling of mixtures, and boiling in heat exchangers and electronic systems, as well as evaporative thermal transport in films, translating/impacting drops, sprays and mists. Some 165 papers dealing with ebullient and evaporative heat transfer are surveyed in this section. The reader may also find reference to these phenomena in the sections entitled Change of Phase—Condensation (JJ), Heat Transfer Applications—Heat Pipes and Heat Exchangers (Q), and Heat Transfer Applications—General (S).

Boiling incipience and bubble characteristics

Knowledge of the conditions required to initiate boiling is of crucial importance in the design of boiling systems. The 1989 archival literature provides an analytic determination of boiling incipience in subcooled water [21J] and in binary solutions [20J], as well as an analytic approach to the determination of the nucleation site density on real surfaces [11J]. The onset of boiling in freely-falling films is examined in refs. [13J, 14J], during flashing flow in refs. [9J, 17J, 18J] and during rapid depressurization in ref. [10J].

The modeling of ebullient heat transfer, as well as the evaluation of the effect of nucleate boiling on surface chemistry and electrical behavior, requires insight into the characteristics of vapor bubbles. Several papers [2J, 8J, 12J, 16J, 19J] examine bubble growth, while refs. [1J, 3J–7J, 15J] provide numerical and experimental results for the physical characteristics of vapor bubbles and the temperature field in the surrounding liquid.

Pool boiling

The traditional concern over the influence of surface parameters and the wetting characteristics of the liquid on nucleate boiling heat transfer are reflected in refs. [24J, 38J, 39J, 52J]. However, much of the recent nucleate pool boiling literature focuses on the behavior of specific liquid families, including: cryogenic liquids for cooling of superconductors [26J, 45J, 49J, 54J] and fluorocarbons for refrigeration cycles and the thermal management of electronic components [32J, 34J, 46J, 53J]. The pool boiling characteristics of saline water solutions [50J], refrigerant mixtures [30J], and organic liquids [23J] are also to be found

Although pool nucleate boiling is the most efficient ebullient heat transfer regime, the design of boiling systems often requires an understanding of the higher wall superheat, transition boiling and film boiling regimes. Experimental observations of pool transition boiling are reported in refs. [22J, 31J, 33J, 51J] and theoretical results in refs. [28J, 43J]. The lower limit of film boiling is explored in refs. [27J, 35J, 41J].

A review of the 1989 archival literature also reveals the results of an analytical and numerical study of film boiling [47J], an experimental study of film boiling in superfluid helium [40J], and measured values for the critical boiling heat flux in ethanol–water mixtures [44J].

Film boiling and transition boiling are of special importance in the quenching of cast materials and the extraction of useful energy from high temperature particles. Boiling behavior during quenching of cast metals is examined in refs. [37J, 48J]. Four articles [25J, 29J, 36J, 42J] examine boiling heat transfer in packed beds or porous deposits.

Flow boiling

The mass fraction and distribution of the vapor phase in flow boiling is known to exert a profound influence on thermal transport along the heated surfaces. Flow boiling data and correlations are, thus, often found to reflect the prevailing flow regime, channel geometry, channel orientation and direction of flow. The flow boiling of fluorocarbons in horizontal channels is discussed in refs. [67J – 69J, 74J, 84J, 93J] and of subcooled water in ref. [57J]. Bubbly flow boiling in vertical channels is the subject of refs. [64J, 76J – 78J]. Ebullient heat transfer rates associated with downflow in single and multiple vertical channels are examined in refs. [62J, 94J]. The interplay of convective and ebullient thermal transport processes and the correlation of flow boiling heat transfer data is discussed in refs. [61J, 65J, 71J, 92J].

The ebullient thermosyphon characteristics of liquid mixtures are investigated in refs. [66J, 82J, 88J]. In ref. [89J], the authors explore water jet impingement on a boiling surface.

Flow of a boiling two-phase mixture gives rise to flow oscillations. The theoretical acoustic characteristics of bubbly two-phase flow are defined in ref. [83J]. The thermofluid instability in a single vertical channel is examined in refs. [75J, 90J, 91J], while oscillations in multiple channels are the subject of ref. [60J].

The critical boiling heat flux (CHF) represents the upper-bound on the highly-efficient nucleate boiling regime and is the subject of extensive research. Theoretical studies of this limiting heat flux are reported in refs. [56J, 63J, 70J, 73J]. Recently published experimental studies of flow boiling CHF include: refs [72J, 81J] — narrow tubes and channels; ref. [80J] — discrete 'chip-type' heat sources; and ref. [59J] — CHF in the presence of power and flow transients.

Imposition of heat fluxes above the CHF value generally results in very high heater surface temperatures and operation within the film flow boiling regime. Thermal transport in this regime along vertical surfaces is studied in refs. [79J, 85J], along horizontal surfaces in ref. [55J], and on plates moving parallel to the flow in ref. [95J]. Articles [58J, 86J, 87J] examine the quenching, by flow film boiling, of rods, molten fuel drops and metallurgical samples, respectively.

Boiling enhancement

The ever-increasing heat fluxes in industrial and electronic equipment continue to stimulate numerous studies of enhancement techniques for boiling heat transfer. The challenge and possibilities for ebullient enhancement are discussed in refs [101J, 114J]. The nucleate pool boiling and CHF results obtained with the use of finned, wire-wrapped, and/or grooved surfaces can be found in refs. [74J, 96J, 99J, 100J, 112J, 113J, 115J]. The influence of grooves on boiling heat transfer in thin liquid films is the subject of refs. [107J, 108J].

Extensive research was undertaken into the boiling characteristics of sintered porous coatings in 1989. Experimental results for water are documented in refs [97J, 106J, 109J]. Article [111J] offers a comparison of pool and flow boiling on an identical enhanced surface and ref. [104J] provides a theoretical model of nucleate boiling on a porous coating. The pool boiling of nitrogen from a sintered metal surface is discussed in ref. [116J]. Other studies address the enhanced boiling characteristics of a surface modified with a perforated polymer film [98J] and a drilled interference plate [110J], as well as surfaces influenced by electric fields [102J, 105J] and ultrasonic waves [103J].

Industrial boiling equipment

The geometric complexity and variety of flow and thermal conditions, encountered in steam and vapor generators, often require extensive study of pre-design and prototype configurations. The thermal and hydraulic behavior of tube-bundle heat exchangers with ebullient heat transfer is examined in refs. [118J, 120J, 122J, 124J, 127J, 129J]. Several 1989 studies explore the effect of fins on boiling heat transfer in channels [119J, 121J, 128J].

The development, design and analysis of nuclear reactors continues to motivate a large number of boiling studies. Critical heat flux in simulated fuel-rod bundles is the subject of refs. [125J, 126J, 130J]. Numerical simulation of post-critical cooling capability is discussed in ref. [123J] and the effect of dissolved gas on boiling heat transfer coefficients in ref. [117J].

Droplet and film evaporation

The evaporation rate of small liquid drops and thin films is often of importance in space conditioning equipment, in liquid fuel combustion, and in the control of airborne pollutants. The need to define the primary parametric trends and to more accurately predict the time-dependence of droplet diameter, film thickness and vapor flow rates has spawned a large number of research studies in this area. The thermofluid characteristics of stationary, or slowly moving, droplets provide a convenient reference plane for the more complex configurations encountered in actual equipment and are described in refs. [138J, 142J, 144J, 149J, 153J] Article [156J] compares theoretical and experimental results for the evaporation of sessile drops of binary liquid mixtures

Droplet evaporation in the presence of relative motion between the phases is studied numerically in refs. [135J, 140J, 141J] and with the aid of a simplified algorithm in ref. [131J]. Experimental results for freely falling nitrogen droplets can be found in ref. [132J] and for aerosols, behind incident shock waves, in ref [151J].

Fundamental considerations in the evaporation of thin liquid films are the subject of refs. [145J, 150J, 154J] Experimental measurements using interferometry to study the evaporation of dilute polymer solutions and laser holographic interferometry to examine the evaporation of water into superheated steam are reported in refs. [134J, 143J], respectively. Articles [147J, 152J] examine convective evaporation inside horizontal and vertical heated channels.

The analysis of thin film evaporation in industrial equipment must deal with several complicating factors The 1989 literature reveals considerable interest in the evaporation of binary solutions — as encountered with oil/refrigerant in horizontal evaporator tubes [157J], lithium bromide/water in absorption refrigerators [137J], organic mixtures in centrifugal molecular stills [136J], and in the study of methanol/ethanol and methanol/water systems [139J]. The thermal characteristics of thin film evaporation in complex geometries are addressed in several additional studies, including wick structures [155J], enhanced surfaces [133J], and along micro-fin tubes [146J]. Direct contact evaporation in spray columns is the subject of ref. [148J].

Sprays and mists

Spray and mist cooling of heated surfaces can provide relatively high heat transfer rates while minimizing fluid flow rates, but an accurate representation of the thermofluid behavior of an individual droplet impacting on a solid surface is a prerequisite to the modeling and analysis of spray/mist cooling systems. References [160J, 161J, 164J, 165J] report on such fundamental studies of droplets The heat transfer rates achieved with both dilute and dense liquid sprays are examined in refs [159J, 162J, 163J] and extended to the cryogenic range in ref [158J]

CHANGE OF PHASE — CONDENSATION

Research in this area includes the following aspects: non-condensable gas effects; effects of unsteadiness, instability and transition; geometrical factors, surface and external influences; papers predominantly on theory and analysis or experimental techniques; condensation in free jet or dispersed droplet geometries; property effects and condensation in binary or ternary mixtures.

Non-condensable gas effects

The investigations of this influence [1JJ–7JJ] are with various gas species and concentrations, in film and bubble geometries, within a porous medium or in conjunction with rough surface effects. Condensation in a porous medium shows an enhanced sensitivity to non-condensables .

Unsteadiness, instability and transition

Studies in this category [8JJ–19JJ] deal with both natural and forced unsteadiness. Several discuss the effects on condensation of flow surges in multipath systems, interfacial wave motion of the condensate in film condensation, acceleration waves on droplet condensation or oscillating shock waves in a steam turbine flow. The effects of forced oscillation of temperature and vapor pressure are analyzed. Conditions for transition from film to drop and drop to film condensation are documented.

Surface and external effects

Studies in this category are on finning and other surface modifications and effects of the environment such as bulk velocity [20JJ–40JJ]. Configured surfaces include profiled rolled tubes, longitudinally and radially finned tubes, tubes with saw-tooth shaped fins, low-finned tubes, tubes with screw-type swirlers, corrugated inner tubes of a double-tube condenser, helical- and circular-grooved tubes and an array of other patterned surfaces. Surface orientation effects include a horizontal plane surface and a downward flowing vapor over a bundle of in-line, staggered tubes. Condensation within a rotating cylinder containing an internal scraper is equivalent to that predicted with a film model using a film thickness of 25 μm. Another study shows that a porous fin is effective in thinning the liquid film. A study of surface chemistry effects shows filmwise condensation on uncontaminated surfaces and dropwise condensation on a surface impregnated with a promoter agent. Another shows the effect of the surface temperature boundary condition on condensation of a pure vapor. External effects include immersion in a granular bed and imposing a bulk vapor velocity or an electric field.

Theory and analysis

Papers in this category appear to be focused on theory, analysis and modeling of condensation [41JJ–52JJ]. In one, the interaction between saturated and superheated steam with subcooled water is investigated leading to the development of a laminar-to-turbulent model. In another, condensation of vapor bubbles in subcooled water is modeled and compared to data. In a third, an interpolation formula for forced flow condensation is proposed. The theory of homogeneous nucleation and methods of its experimental investigation are discussed. Modeling of interfacial forces; subcooling, superheating, bulk velocity and non-condensable effects and special concerns in heat pipe condensers are attempted in various papers. An analogy between condensation on a vertical wall and on a horizontal tube bundle, a two-fluid model of filmwise condensation, direct statistical modeling and Prandtl's hypothesis and Reynolds' analogy are implemented in papers within this category

Experimental measurements

Papers in this category appear to focus on experiments and experimental techniques [53JJ–57JJ]. Documentation of condensate film and vapor flow patterns is the most common theme. However in one paper, dropwise condensation on a PVC surface is studied in detail using an interference microscope/laser beam technique.

Droplet and free jet condensation

The droplet and free jet flow geometries are investigated in several papers [58JJ–68JJ]. The jet papers deal with coherent and fragmenting, laminar and turbulent jets of subcooled liquid Details such as the effects of the exit velocity distribution and transition to droplet flow are included. In one paper, a contrast between jet and droplet condensation is made. Several papers investigate the details of condensation of single droplets, one by investigating condensation on 'new' surfaces

Property effects

Property effects studied in last year's literature include the Marangoni effect resulting from surface tension gradients, the viscosity gradient effect, the effect of absorption of soluble gases, the effect of an endothermic soluble heat-absorbent and non-equilibrium effects [69JJ–76JJ]. Papers on non-equilibrium effects include a comparison between integral and differential condensation, condensation of bubbles in subcooled flow and homogeneous nucleation.

Binary and ternary mixtures

Several papers investigate the condensation behavior of binary and ternary mixtures [77JJ–83JJ]. They include such combinations as chlorofluorocarbon mixtures, ethanol and water, fluoroalcohol and water and a ternary mixture of methanol, ethanol and water The fluoroalcohol and water mixture is considered to be a good candidate replacement fluid for use in Rankine cycles. Geometries and special concerns include film condensation in vertical tubes, dropwise, drop and streak, and ringwise condensation; and turbulence generated by a wavy interface.

CHANGE OF PHASE — FREEZING AND MELTING

During recent years, much interest has been devoted to the modeling and analysis of problems involving a change of phase — a phenomenon which takes place in many processes of technological interest to include solidification of various forming processes, freezing and melting, applications to crystal growth, castings, etc. Subcategories in this general area include: Stefan problems, solidification in casting processes, crystal growth, studies of freezing and melting, convection effects during solidification, numerical/analytical models and experimental investigations, and the like.

Stefan problems

The classical Stefan related problems have long been an active area of continued investigations for solidification related problems Papers in this subcategory involve studies of the generalized Stefan problems, two-phase Stefan models, and multidimensional solutions and approximations [1JM – 4JM].

Solidification of alloys/metals and casting processes

Numerous papers (theoretical, numerical, and experimental investigations) appear dealing with aspects of phase change in alloys and metals and casting processes Studies also included shrinkage effects, investigations in enclosures, arbitrary shaped bodies, anisotropic effects, dissimilar materials, heat source/sink effects, and the like. Specific papers dealing with enclosures appear in refs [6JM, 9JM–11JM, 13JM, 16JM, 20JM, 22JM, 30JM, 31JM] Those dealing with other general issues of solidification appear in refs [5JM, 7JM, 8JM, 12JM, 14JM, 15JM, 17JM–19JM, 21JM, 23JM–29JM]

Solidification — crystals

There has been an increased research activity this past year in solidification issues relevant to crystals and crystal growth phenomenon. Investigations encompass crystal growth simulations, directional solidification, kinetic aspects, buoyancy and surface tension effects, growth dynamics, and stresses induced during solidification [32JM –49JM].

Freezing and melting. frost, ice, and snow

Research in freezing and melting emphasizing ice crystal growth, frost formation in tube-array evaporators, flow-fields over ice accretion shapes and surface water behavior, deicing of aircraft components appear in refs. [50JM–56JM]

Freezing and melting: applications

Related applications dealing with contact melting and friction, thermal interaction of pipes with frozen soils, and other freezing and melting issues appear in refs. [57JM–62JM].

Convection effects

Numerous theoretical and experimental investigations dealing with effects due to convection during solidification have been addressed. Of concern were forced convection effects, thermosolutal convection, natural convection, melting of binary mixtures with double-diffusive correction, solid–liquid phase change involving surface tension driven convection, and magnetic field influences on convective heat transfer during solidification [63JM–77JM].

Continuous casting processes and mold filling

Numerical simulations in continuous casting processes appear in refs. [79JM, 80JM]. Effective thermal conductivity considerations in continuous casting appears in ref [78JM], and applications of mathematical models to a continuous slab casting mold appear in ref. [82JM]. The modeling of fluid flow and heat transfer during mold filling is addressed in ref [81JM]

Numerical simulations

Computational methods and simulations dealing with eutectic crystal growth, heat transfer calculations during melting of pure substances, finite element simulations of heat flow in continuous castings, and numerical studies of free and forced convection appear in refs. [83JM–89JM]

Miscellaneous applications

Groundwater flow effects in processes of soil freezing are addressed in ref. [104JM] Temperature distributions induced by heating with line-shaped electron beams is presented in ref. [106JM]. Numerous other aspects involving phase boundary motion and phase transformations, subcooling or undercooling effects, thermal energy storage units, consolidation and thawing of frozen soil, etc , are described in refs. [90JM–103JM, 105JM, 107JM]

RADIATION IN PARTICIPATING MEDIA AND SURFACE RADIATION

Participating media studies

This first section includes two review articles, studies in one-dimensional participating media, and various suggestions for approximate or improved solutions of the radiative transfer equation [1K–19K]. The review articles cover radiative transfer in dispersed media and experimental techniques for gas fluidized beds. Improved solution techniques for dispersed systems, for applying Galerkin's method, and numerical integration are suggested. Scaling, diffraction-scattering subtraction methods and an inverse radiation analysis are also presented. Radiative transfer in semi-infinite layers, planar layers, cylindrical and spherical media, a non-equilibrium nitric oxide synthesis reactor are investigated. The types of media considered include porous layers, layers with reflective boundary, statistical media, anisotropic scattering media, strongly-fluctuating continuous random media, and particle-gas layers

Multi-dimensional radiative transfer

New formulations for multi-dimensional radiative transfer and solutions for particular geometries are considered in this section [20K–33K]. Rectangular enclosures received the widest attention with published numerical results that range from approximate to benchmark accuracy. Other geometries considered are two-dimensional cylindrical media, conical enclosures, and finite clouds. New formulation of the modified differential approximation, integral formulations for anisotropic scattering media, double integration formulation of Ambarzumian's method, and product-integration method applied to discretize the integral equation are described.

Radiation combined with conduction

Various techniques are used to analyze radiation–conduction interactions in flat glass, in media of different refractive indices, non-gray gases, concentric cylindrical media, and scattering media [34K–40K] Temperature, flux, and mixed boundary conditions are considered by using such techniques as Hottel's zone method extended by ray tracing, nodal approximation, and spherical harmonics approximation

Radiation combined with convection

Combined radiation and convection problems are studied in the following papers [41K–52K]. Some of the studies consider laminar channel flow of non-gray gas, two separated layers of different refractive indices, boundary layer flows, buoyancy induced channel flow, and flow in porous medium. Thermocapillary motion, thermal stability, heat transfer in solid rockets, rarefied gas flow, and cylindrical gas reformers are also investigated Radiation in high speed flow is included in the section on "Miscellaneous radiation studies" .

Surface radiation

Most of the works in this section deal with evaluation of view factors [53K–62K]. Among the many techniques presented, the Monte Carlo technique is used for determining the view factors and is also applied to a radiative heat transfer calculation Theoretical scattering from surfaces and the engineering model of surface specularity discussions are also included in this section.

Engineering radiative properties

Most of the papers in this section present emittance, transmittance, and reflectance data [63K–79K]. Emissivities of metals, non-metals, composite systems, reflectances of environmental surfaces to solar radiation, and transmissivity through water droplets and a randomly-packed bed of spheres are some of the data presented There are discussions of an emissivity measurement technique, and measurement of surface temperature with the emissivity during laser irradiation. Effective optical properties for approximate radiative transfer calculations, experimental determination of radiative transport properties of particulate and porous media, and electromagnetic levitation with acoustic modulation are also considered.

Light scattering from particles

Studies of light scattering from particles and particle systems are included in this section [80K–92K]. The types of particles considered are rough, non-spherical Chebyshev, crystals, and fibers of different orientation.

The particle systems considered are branched chains of aerosols, three-dimensional lattice of spheres, aerosol in heated air, and particles in dilute and dense suspensions.

Radiation in flames and combustion systems

Topics considered in this section include: turbulence/radiation interactions in flames, radiation characteristics of explosions, effect of radiation on thermal ignition, focused laser beams on aerosols, measurements in pool fire, flame spread on wood with irradiation, and modeling of thermal radiation in industrial furnaces [93K–107K].

Combustion of coal and soot properties

Studies of soot properties in isothermal layers, in elongated form, surrounding a coal particle, as well as the effect of the H/C weight ratio on optical properties are studied [108K–116K]. The effect of particle radiation and flyash properties on pulverized coal fired boilers are investigated. Optical constants of coal slags and the combustion of coal aerosol by intense optical radiation are also considered.

Radiative transfer in gaseous media

The correlated-k method for inhomogeneous atmospheres is one of the topics in this group of papers [117K–122K]. Gray and non-gray gas models used for radiative heat transfer calculations are compared. Analyses involving NO and steam at high pressures illustrate the importance of accurately specifying the spectral properties of the gases. Studies involving radiative transfer in non-gray gases can also be found in other sections of this review, e.g. "Radiation combined with conduction or convection".

Radiative property of gases

Absorption characteristics of gases such as N_2O, NO, CO_2, methane, ethylene, propane, are presented in terms of line strengths, width, and profiles [123K–142K]. Some of the properties are correlated into narrow- and wide-band models. A table of Voigt functions is also presented.

Miscellaneous radiation studies

This section includes the papers [143K–166K] that deal with a variety of topics: blackbody radiation, devices such as bolometer arrays and photoacoustic cell for measurement of absorption line profiles, radiation in high speed flows and in various energy systems, transient radiative cooling from a single sphere and from liquid drop radiators, Chandrasekhar's X-, Y- and H-functions, and response of materials to intense radiation.

NUMERICAL METHODS

As in recent years, numerical methods are being increasingly developed and applied to a wide variety of practical problems. In this review, the papers that focus on the application of a numerical method to a specific problem are included in the category appropriate to that application. Papers that deal with the details of a numerical method are reviewed in this section.

Heat conduction

Numerical methods for heat transfer are often applied to heat conduction as it provides a convenient testing ground for new techniques. Both direct and inverse heat conduction problems have been analyzed by the methods described in refs. [1N–23N]. The methods are primarily of the finite difference or finite element variety, some papers deal with the boundary element method. The use of boundary-fitted grids is increasing. The papers deal with steady and unsteady problems. There is considerable progress in constructing more accurate and more efficient methods. Adaptive grids are used in some papers.

Phase change

The phase change problems are usually treated as an extension of a heat conduction problem with an appropriate calculation of the solidification front. Papers dealing with the Stefan problem and other phase-change situations have appeared [24N–27N].

Convection and diffusion

The transport of a flow property such as enthalpy, momentum, or concentration is influenced by the processes of convection and diffusion. A proper treatment of these processes is essential for the success of a numerical method. In papers dealing with convection–diffusion formulations [28N–50N], new schemes have been increasingly worked out for the finite element methods. Some papers explore the use of multigrid techniques, boundary element methods, flux-corrected transport, and Eulerian–Lagrangian splitting. Some comparisons of a number of schemes on a set of test problems have been published.

Flow equations

A large number of papers deal with the development, modification, improvement, and testing of numerical methods for the calculation of fluid flow and associated processes [51N–82N]. The application areas include forced flow and natural convection, compressible and incompressible flows, and laminar and turbulent flows. Both finite element and finite difference methods have been used; some use of the boundary element method has also been reported. Among the numerical issues are: parabolic or partially parabolic formulations, multigrid techniques, grid staggering, and boundary-fitted coordinates.

General techniques

Techniques for solving simultaneous algebraic equations, new finite element interpolations, and moving finite elements are described in refs. [83N–87N].

TRANSPORT PROPERTIES

Investigations in this category concentrate markedly on measuring and predicting thermal conductivities and diffusivities for a wide variety of materials, some of which are used at extreme temperatures.

Thermal conductivity

For obtaining thermal conductivity and specific heat values for liquids and gases various techniques are used: spherical calorimeter, parallel-plate apparatus at pressures up to 150 MPa and temperatures down to 77 K, and hot wire measurements on noble gases at 25°C and pressures up to 1 GPa [15P, 18P, 19P]. Using the kinetic theory of gases a general correlation gives the thermal conductivity at low density in terms of known quantities: other gas properties, structural parameters and interaction quantities [26P]. For improving conductivity measurements a model is proposed for calculating heat leaks through the powder packing [10P]. For solids a method is described for obtaining conductivity values from measured temperature profiles, a non-local theory of thermal conductivity is derived for heat transport by phonons and a survey of measurements for the conductivity of non-metallic materials under pressure is reported [16P, 21P, 25P]. At high temperatures an apparatus for measuring the temperature dependence of the conductivity of small specimens in the range 8250 K is described and kinetic theory applied to a magnetized one-component plasma to study longitudinal and transverse heat conductivity and to mixtures of reacting gases to calculate transport processes [1P, 2P, 12P, 23P].

A number of works focus upon the particular material conductivity because of its importance in applications or in illuminating the relationship between transport properties and molecular characteristics. In the former instance the conductivity of copper powders of different particle size is measured by the transient hot strip method. Macor (a mica glass ceramic) and staybrite (a stainless steel) conductivity is measured below 1 K; a method of studying thermophysical characteristics of ceramics at high temperatures (1800 K) is described in refs. [3P, 5P, 17P, 29P]. Other papers report results for special materials: moist, unsaturated, baked clay, ceramic and graphite fiber thermal insulation in mat form, semitransparent materials (e.g. glass and metallurgical slags at high temperature, thermal super insulations, and alkali-metal liquid and vapor [8P, 11P, 22P, 24P, 28P]. Conductivity measurements on chlorobenzene (moderately polar) and analysis of data for glassy As_2Se_3 provide theoretical insights [13P, 20P].

Porous media conductivity is the focus of several studies. The non-steady-state probe is modeled and the effective thermal conductivity of high temperature particulate beds is measured and compared with predictions [6P, 7P, 27P]. At low temperatures experiments are described for measuring conductivities for pure metals and elastomers and for reducing heat loss from cryogenic pipelines [4P, 9P, 14P].

Thermal diffusivity

Determinations by analysis are obtained for rare gases and methane using data available and corresponding states principle, for composite media by computer simulation and for silica fibers, soil under various conditions and molybdenum [33P, 35P, 39P, 43P, 44P, 46P]. Thin, two-layer metallic plate diffusivities are studied as well as thin-film samples bonded to transparent substrates. Methods used are plane temperature wave analysis and interferometric calorimeter [37P, 38P, 42P]. Other measurement schemes employed are hot wire and hot strip for selected organic and polymers, and a fast non-steady method using parameter estimation [31P, 34P, 36P]. In the region of high temperature a laser flash method is used to measure diffusivity of iron pellets. Iron of various purities, high performance corundum insulation, and heat shields–thermal insulators are studied, as is the basic transport of energy by electron–electron interaction [30P, 32P, 40P, 41P, 45P].

Viscosity

Several papers report measurements of viscosity using a variety of methods: argon using a vibrating wire viscometer, sulfur hexafluoride by an oscillating-disk device and dilute polymer solutions employing a new high temperature capillary design [49P, 51P, 52P]. Material concerns lead to the measurement of viscosities of crude oils and their mixtures, the calculation of the effective viscosity of suspensions and emulsions of spherical particles, and the gas permeability of sintered aluminum matrix [47P, 48P, 50P]. The advantages of a new modification of Enskog's theory is demonstrated by calculating monatomic gas viscosity [53P].

Thermodynamic properties

The continued need for PVT and liquid–vapor equilibrium data continues to attract the interest of investigators. A new variable volume method for non-reacting fluids and fluid mixtures is described and results for chlorodifluoromethane and sulfur hexafluoride presented. Other works report measured PVT properties of light and heavy water and calculated thermodynamic properties of nitrogen using the Benedict–Webb–Rubin state equation. For multi-component, multi-phase systems the temperature of a wetted bulb is modeled, and a computer program reported for calculating psychrometric properties [54P, 60P, 61P, 63P, 64P]. By joining theory and experiment several papers attempt to maximize the utility of predictive schemes for determining transport and equilibrium thermodynamic properties of fluids [56P, 58P, 65P].

For heat capacity determination of small samples a modified heat-pulse technique is given, a rapid measurement scheme for single submillimeter particles, and a microcalorimeter for liquids [55P, 57P, 62P]. At high temperatures platinum–rhodium alloy heat capacities were measured and magnetocaloric effects studied in thulium [59P, 66P].

HEAT TRANSFER APPLICATIONS — HEAT EXCHANGERS AND HEAT PIPES

General, tube bundles, shell and tube

Continuing research in this area embraces a wide variety of special operating circumstances and applications. For tube assemblies, topics considered are pressure drop, convective exchange for liquid sodium flow over tube-banks, non-condensable gas effects and particulate presence. Further consideration is given to the performance of split flow exchangers, compact exchangers, relation of geometry to effectiveness, orientation, non-Newtonian fluids, and the correlation between steady-state and dynamic response for counter flow exchangers. Also covered are shell and tube exchangers with different *NTU* values in each tubeside pass, a model with different turbulence models for shell-side flow, an open cavity natural convection exchanger, and plate exchangers. Transient analysis of heat exchangers and image processing theory and a historical perspective on heat exchangers are noteworthy [1Q–17Q]

Fins and extended surfaces

The characteristics and performance of a number of schemes for augmenting heat transfer in exchangers are reported helically finned tubes, twisted tubes, louvered fins with overlaid grids, gilled pipes and membrane heated surfaces, wing type vortex generators, triangular lattice with liquid-metal coolant and short-protrusion rectangular fins. Other effects influencing finned surface performance include fin material and thickness, shape drag of finned tube bundles, effect of swirl pipes, flow about the tip of bayonet tubes and entry region heat transfer in turbulent flow. Other works examine steady-state and dynamic simulation of plate fin exchangers and the first/second law cost analyses of enhanced heat transfer surfaces In the area of air-conditioning, louvered finned exchangers are the subject of a three-part study, as well as the effect of frost growth on performance and assembly of partially segmented plates. The comparative service of rippled fins and interrupted fins and 3-D heat transfer in arrays of heated square blocks conclude the work in this category [18Q–41Q]

Evaporators, boilers, condensers, recuperators

Cooling towers are studied by a number of investigators design of dry cooling towers by cost-optimal analysis and by the effectiveness–*NTU* method, and dimensioning heat exchangers for extant towers (dry). Basic processes are examined for evaporation rate in a falling film For boiling processes natural circulation boiler systems are treated as well as the modeling of vapor generators by design codes for conventional types and nuclear reactors. Heat transfer in furnaces considers the simulation of coupled modes (radiation and convection), a cylindrical configuration with radiative recirculation, the importance of tube position on uniform heating, and convection in IR furnaces Condensing phase change studies include water vapor condensation on rotating and fixed tube banks, a method for measuring simultaneously the fouling factor and water velocity in a condenser tube, R-12 condensation in a shell and tube (plain and low fin) condenser, and a dynamic model of a condenser [43Q–47Q, 49Q, 51Q–53Q, 56Q, 58Q, 59Q, 62Q, 63Q, 65Q–67Q, 69Q, 71Q].

Regenerative heat exchanger papers report the effect of longitudinal heat conduction, condensation in cross-counter flow gas-to-gas exchangers, performance with changing flow regime, and the maximization of heat recovery in air-to-air exchangers. A number of numerical analyses examine the periodic behavior of exchangers, rapid calculation schemes, and transient behavior [42Q, 48Q, 50Q, 54Q, 55Q, 57Q, 60Q, 61Q, 64Q, 68Q, 70Q]

Contact exchangers, bubble columns, rotating surfaces, fluidized/packed beds

For contact exchangers results are reported for enhancing transfer in gas–liquid units, the performance of a three-phase spray column, the stability of a spray column exchanger, and the numerical analysis of liquid–liquid systems [75Q, 77Q, 79Q, 81Q, 90Q]. For bubble columns attention is focused on exchange between liquids and suspensions with stirring, heat transfer from a cylindrical probe, the heat transfer mechanism itself, and heat exchange in slurry reactors [76Q, 88Q, 89Q, 93Q]. The influence of surface rotation on heat exchange is considered in a number of works. two-coaxial cylinders (one cylinder rotating), mixed convection over rotating bodies, particle rotation as a heat transfer mechanism and falling particles in rotary dryers. Rotary kilns are modeled and convective tunnel kilns optimized [72Q–74Q, 78Q, 85Q–87Q, 91Q, 92Q]

Packed bed regenerators are examined for two-dimensional effects, convective exchange in porous enclosures, numerically modeled, and considered for replacing double-pipe exchangers [80Q, 82Q–84Q].

Analysis, optimization, design codes

A number of criteria are used in the analysis of heat exchangers for optimum service. maintenance cost, thermal efficiency, second law analysis in the case of non-equilibrium fluid streams, irreversibility minimization, available energy, entropy production and regenerator effectiveness. Other works describe design codes, developed through mathematical analysis and subsequently validated, and examine *NTU* formulas as they apply to multipass heat exchangers and their effectiveness For optimal synthesis of heat and power cogeneration systems 'pinch' and operating line methods of analysis are compared [94Q–107Q]

Heat pipes

Experiments explore a range of heat pipe phenomena. flow patterns and heat transfer process in vertical closed and open systems, capillary limit and vapor flow analysis for a concentric annular heat pipe, effect of localized heat input on performance and the influence of geometry on closed tube units at low Rayleigh numbers Other measurements address the sodium heat pipe, the effect of large length–diameter ratios, the behavior of a variable conductance using a binary mixture of refrigerants and corrugated tube devices

Analytical studies consider the screen wick heat pipe and factors influencing its operation, the suppression of the sonic heat transfer limit in high temperature units, numerical and analytical solutions for 2-D gas distribution in gas systems, and the effects of conjugate heat flow, vapor compressibility and viscous dissipation on operation. The design and performance of the closed-tube aerosyphon is described and the heat transfer examined in molten salt reactor designs [108Q–126Q].

Special applications

A number of papers concern rather specialized applications of heat exchangers. Thus a thin film design with agitation is reported to minimize fouling in dairy processing; performance of matrices for Stirling engines is tested, and high temperature regenerative exchangers for MHD power generation are studied A ceramic exchanger for industrial furnaces is developed and a regenerator for cryogenic refrigerators designed For regenerators using combustion products as the hot stream deslagging and slag minimization are chief concerns [128Q, 130Q, 131Q, 133Q, 142Q, 143Q, 147Q, 151Q, 152Q].

Vehicle and room radiators are tested and storage space-heating designs proposed and compared. Electric heating is used to preheat air for subsequent experimental purposes and to melt metalized pellets in steel making For air-cooled heat exchangers the air flow is simulated numerically and the effect of frost formation examined. Fouling by particulate matter continues as a concern. Sorption heat transformers using zeolites as solid absorption agents extend the working temperatures of these units [127Q, 129Q, 134Q, 135Q, 138Q–141Q, 144Q, 146Q, 154Q]

Critical heat flux for upward cross flow of R-113 on horizontal tubes is studied, and for radiative exchangers the heat transfer is optimized for concentric heating elements. A method is presented for optimizing the thickness of air-duct insulation for minimum costs Manifold-shaped cooling systems of varying geometries are analyzed and the characteristics of feedwater heating in power plants discussed. A selection process which incorporates optimum pressure drop and fouling in exchangers during conceptual design is reported to improve operating efficiency of process plants [132Q, 136Q, 137Q, 145Q, 148Q–150Q, 153Q]

HEAT TRANSFER APPLICATIONS — GENERAL

Papers in this category are arranged in sections according to the applications in which heat transfer is involved. Approximately two-thirds of the identified papers are included and preference is given to those containing experimental information. The sections are now discussed in sequence according to the number of publications starting with the one indicating the largest research effort. The numbers beside the subtitles refer to the listing in the bibliography

Manufacturing, processing [1S–47S]

Papers in this section included among others the field of casting, welding, cutting, drilling, quenching, vapor spray deposition, and melting considering metallic materials and polymers. The structure of steel was altered by chill casting. Constant melting point powders were used to evaluate the temperature distribution in metal cuttings. A heat pipe improved the performance of lathe tools Similarity analysis was used to study injection casting

Buildings, ground [48S–65S]

Publications in this area include papers on heat transfer through roof constructions, windows, floors and typical houses. They describe the evaluation of the air temperature distribution in air conditioned spaces, and heat flow in the ground Heat and moisture transport in fires is also discussed. Energy savings are obtained in windows by filling the space between the panes with a low conductivity gas. Methods to measure thermal transmittances of envelopes of buildings are discussed.

Refrigeration, cryoengineering [66S–80S]

Papers in this section deal with air conditioners and refrigeration plants, and in a larger group of publications with superconductors, cryocoolers and heat transfer in helium II and IV. A new method of high performance cool energy storage using ice is proposed. High temperature ceramic superconductors in subcooled supercritical nitrogen have special heat transfer characteristics.

Boilers, reactors [81S–93S]

This section deals with heat transfer in furnaces and in various kinds of reactors such as rotary, moving bed pyrolyser, CVD and bioreactors. The corrosion on the refractory walls of a furnace is calculated. Radiative nets reduce the energy consumption in industrial furnaces. A correlation is proposed for heat transfer in bioreactors.

Electronics [94S–105S]

The papers in this section deal with the cooling of electronic equipment by heat transfer with air or liquid, describe a new technique to cool microcomputers, measure heat transfer coefficients of packages in helium filled disk enclosures, and study forced convection in production by soldering or welding.

Bioengineering [106S–116S]

The heat and mass transfer from individuals caused by warm and hot exposure, by hyperthermia have been measured. Enhancement of heat transfer to red cell suspensions in laser irradiated tissue, and in the liver is discussed. A model is used to calculate the heat generation rate within a tissue irradiated by a laser.

Nuclear engineering [117S–127S]

Experiments studied the thermal and hydraulic performance of the fuel blocks of high temperature gas cooled reactors A heat transfer and flow visualization experiment established the thermal state of spent fuel transfer buckets and storage casks. High heat flux components in fusion reactors were investigatea

Gas turbines [128S–136S]

The turbine blades as one of the most significant elements in a gas turbine received attention by various thermal analyses. Experiments determined heat transfer in the channel of an internally water cooled gas turbine blade and a steam cooled return flow blade. Studies on combustors were concerned with the prediction of the convective and radiative heat flow and provided also experimental information A review describes laminated porous walls, angled multihole cooling, and composite metal matrix cooling of combustor liners. A computational procedure to calculate the nozzle temperature in turbofans is proposed

Piston engines [137S–145S]

Local heat transfer coefficients on chamber walls of gasoline engines have been measured. A computer analysis predicts the local temperature field of the piston in good agreement with temperatures measured on an operating engine. Numerical analysis treated heat transfer in piston engines with divided combustion chambers, in ceramic, and in ethanol engines. Analysis and experiments clarify the unsteady heat transfer in the Stirling engine.

Drying [146S–153S]

The drying process of various materials like wood chips in ambient air, agitated granular beds, equations for drying curves and minimum energy cycles, as well as porous and freeze drying are discussed. Saline water is dried when exposed to high fluxes of air ions produced by corona electrodes.

Aeronautics, astronautics [154S–159S]

Interaction between the flow, heat transfer, and deformation of panels heated by a 6.6 Mach number flow was analyzed by a finite element approach. Spacecraft interactions with the harsh environment are claimed to be similar to high temperature vaporization and oxidation and lead to ablation even when the surface temperature is low. The thermal control system was designed for a shuttle-launched experiment to map X-ray sources in space. Use of two heat rejection temperatures instead of one for spacecraft heat pumps reduces waste heat rejection. The cooling temperature plume in the presence of uniform and non-uniform cross flow has been measured and the transient temperature in a cooling pond analyzed.

Tribology [160S–165S]

A model for analysis of the thermal flux distribution in unlubricated friction processes has been used to determine the contact surface temperature and wear intensity The temperature field in a brake disk has been calculated and the results were verified experimentally

Rockets [166S–170S]

O-ring erosion in solid rocket models is found analytically highly dependent on the impingement jet temperature and the available fill volume. A similar analysis treats the carbon nozzle regression in solid propellent rockets Agreement with experimental results is obtained, when the boundary layer on the originally smoother rocket wall is assumed laminar but changing to turbulence with roughening of the ablating wall Turbulent transport in ram jet combustors is analyzed numerically Heat transfer and velocity measurements of single and two-phase flows in a model gun are described.

Cooling towers, ponds [171S–173S]

Wind tunnel experiments determined the temperature of cooling tower plumes in the presence of uniform and non-uniform cross flow The transient temperature field in a cooling pond was analyzed.

SOLAR ENERGY

Large central systems

Evaluations of the performance of large central solar energy systems included the central receiver pilot plant in Barstow, California [3T], the Themis central receiver plant at Targasonne, France [1T, 2T], and both a central receiver plant and a hybrid mirrors plant in Japan [4T].

Collectors

The thermal behavior of non-concentrating solar collectors was studied by numerous investigators. The effects of radiation conditions and collector orientation [23T, 26T] and methods for evaluating performance [22T] and heat loss [18T] were described. Alternative collector strategies were studied, including 'reverse plate' [21T], compound and composite configurations [6T,12T], addition of triangular fins [19T] and multiple collection temperature settings [13T].

Absorption of solar energy in various types of receiver cavities was analyzed [7T, 10T, 20T, 24T, 25T, 27T, 28T] Two studies of fluidized bed collectors were described [11T, 14T]. Several papers examined parabolic concentrating collectors [8T, 9T, 15T–17T], and one evaluated a stretched-membrane mirror module for central receivers [5T]

Air heaters and dryers, and water heaters

The International Energy Agency/Small Solar Power Systems volumetric receiver, which heats air by flowing ambient air through the wire mesh layers of a solar absorber, was studied both experimentally and theoretically [44T] Other air heaters studied included a matrix-type porous absorber [36T], a semi-transparent packed bed [39T], and a flat plate with or without augmented surfaces [35T]. Use of solar dryers was described for use in rural areas of China [40T] and India [30T].

Solar water heaters were the subject of numerous papers, including three on thermosyphon systems [29T, 37T, 38T], one on a self-pumping boiling collector system [31T], various other systems studies [32T–34T, 42T, 43T, 45T], and a study of the effectiveness of differential temperature control [41T].

Passive heating, energy storage, and solar ponds

A method was presented for predicting cooling loads in passively heated buildings [52T], and passive heating was simulated in an experimental study involving a cubic test box [48T]. Papers on energy storage included studies in which the storage medium was a homogeneous wall [47T], the ground [56T], liquid tanks [46T, 49T], and a hollow cylinder [54T], as well as storage systems utilizing the heat of fusion of nitrate salts [55T] and the heat of dilution of a sulfuric acid–water system [53T] Salt-gradient solar ponds were studied [50T, 51T]

Miscellaneous applications

Papers which discussed specific applications of solar energy included studies of systems for production of biogas [64T, 65T], a solar furnace for chemical synthesis [61T], a solar regenerator as part of a cooling system [58T], a solar heat pump system [57T], greenhouses [59T, 60T], solar stills [66T, 67T], solar cookers [62T], and a solar-heated indoor swimming pool [63T].

PLASMA HEAT TRANSFER AND MHD

Plasma heat transfer, with emphasis on materials processing applications

Heat transfer is central to several materials processing techniques involving thermal plasmas. Plasma–particle heat transfer was studied in the context of plasma spraying [5U, 12U], in which the object is to melt individual particles before they impinge on a target substrate Melting of bulk surfaces was studied in relation to metallurgical applications [8U] and to electrode wear [6U] Plasma heat transfer in welding was studied both for arc welding [11U] and for laser keyhole welding [3U]. In many cases arc behavior is itself affected by heat transfer to a surface, as in ablation arcs [9U, 10U] or in the effect of cathode evaporation on a free-burning arc [4U] Fundamental studies of plasma heat transfer included a review of models for collisionless one-dimensional flow to a surface [1U], heat transfer between a surface and a low-pressure d.c. plasma jet [7U], heat transfer to smooth bodies in the flow of hypersonic rf induction plasmas with chemical nonequilibrium [13U], and heat transfer to thin films exposed to electron beams [2U]

Heat transfer in MHD and EHD flows

Magnetohydrodynamic (MHD) and electrohydrodynamic (EHD) flows, which involve the flow of electrically conducting fluids through magnetic (MHD) or electric (EHD) fields, exhibit a fascinating variety of heat transfer problems. Several different aspects of MHD heat transfer were reported, including flow with porous walls [16U, 21U], wavy walls [22U], two-phase flow [19U], liquid metal flow [20U], free convection and mass transfer to a vibrating vertical cylinder [14U], and an analytical study of the effect of Hartmann number on heat transfer [24U]. The cooling of temperature-sensitive magnetic fluids in a magnetic field was examined in two studies [17U, 23U] Heat transfer in railguns was investigated [18U]. A corona torch generates an EHD flow, with interesting heat transfer effects [15U]

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