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Heat transfer—a review of 1995 literature

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1. Introduction

The present review of the heat transfer papers published in 1995 is intended to encompass the English language literature, including some translations of foreign language papers. It categorizes and briefly surveys a large number of fields of heat transfer. The survey, although intensive cannot encompass every single paper; some selection is necessary in most of the sections of the review. In addition to the reviews of 1995 journal publications, we briefly summarize conferences that included a number of heat transfer papers as well as mention some of the major awards given in the heat transfer field and list heat transfer books published during the year.

Several meetings were conducted under the auspices of the International Center for Heat and Mass Transfer (ICHMT). A symposium on Severe Reactor Accidents, conducted 21–26 May in Cesme, Turkey, considered heat transfer aspects of accidents in nuclear power plants particularly due to reactor core and primary system flow failures. Heat transfer problems in power engineering were reviewed in an ICHMT Seminar on 'Heat Transfer Enhancement in Power Machinery' conducted 26–30 May in Moscow, Russia. An ICHMT Symposium on Radiative Heat Transfer held in Kusadasi, Turkey on 14–18 August, included combustion systems, measurement techniques, modeling and inverse radiative transfer methods. The 4th U.K. National Conference on Heat Transfer was held 26–27 September in Manchester, England. The conference included sessions on radiation and combustion, convection, two-phase flow, condensation, pool and flow boiling, numerical techniques in modeling, heat exchangers and heat transfer augmentation. The 2nd Indian Society of Heat and Mass Transfer—American Society of Mechanical Engineers (ASME) Heat and Mass Transfer Conference was held in Surathkal, India and encompassed a variety of areas in heat transfer. The ASME Turbo Expo '95 Conference held in Horcation, U.S.A., 5–8 June included multiple sessions on film cooling, internal cooling and external heat transfer in gas turbine systems. The 30th National Heat Transfer Conference, organized by ASME, in Portland, Oregon, U.S.A. on 5-8 August, contained multiple sessions on basic aspects of two phase flow and heat transfer, multiple-phase flow in waste management and environmental restoration, interphase transfer with particles combustion and fire research, cooling of electric systems and subcooled flow boiling. The International Mechanical Engineering Congress and Exposition, held by ASME 12–17 November in San Francisco, U.S.A., included multiple sessions on heat transfer in biological systems, high heat flux heat transfer, material processing and manufacturing, multi–phase heat transfer, heat transfer in environmental flows, multiphase transport in porous media, as well as sessions on fire and combustion research, numerical methods in heat exchanger design, computational studies, development of heat transfer benchmark problems and heat transfer in nuclear waste storage systems.

Other conferences of interest in 1995 included the 19–24 March ASME/JSME Thermal Engineering Conference in Hawaii, the 9th International Conference on Thermal Engineering and Thermogrammetry held 14–16 June in Budapest, Hungary, and a special symposium on Thermal Science and Engineering in honor of the 60th Birthday of Chang Lin Tien held in Berkeley, CA.

The 1994 Max Jakob Award (presented in 1995) was awarded to Geoffrey F. Hewitt of Imperial College, London, England, for his many contributions particular to multi-phase flow and heat transfer systems. The 1994 Kern Award was given to Joseph Balen, while Heat Transfer Memorial Awards were given to John R. Lloyd of Michigan State University for the Art of Heat Transfer and Yogesh Jaluria of Rutgers University for the Science of Heat Transfer. The 1994 Luikov Medal (given in 1995) of ICHMT was awarded to Maurizcio Cumo of the University of Rome, Italy.

Books published in 1995 on Heat Transfer are listed below.

Advances in Heat Transfer Vol 26
James P. Hartnett, et al.
Advances in Heat Transfer: Radiative Heat Transfer by the Monte Carlo Method Vol 27
Wen-Jei Yang, et al.
Computational Heat Transfer: The Finite Difference Methodology Vol 2
A. A. Samarskii, P. N. Vabishchevich
Convective Heat Transfer
Sadik Kakac, Yaman

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Design and Analysis of Heat Sinks
 Allan D. Kraus, Avram Bar-Cohen
Handbook of Thermal Conductivity: Organic Compounds C1 to C4 (Library of Physico-Chemical Property Data) Vol 1
 Carl L. Yaws
Handbook of Thermal Conductivity: Organic Compounds C5 to C7 (Library of Physico-Chemical Property Data) Vol 2
 Carl L. Yaws
Handbook of Thermal Conductivity: Organic Compounds C8 to C28 (Library of Physico-Chemical Property Data) Vol 3
 Carl L. Yaws
Heat and Mass Transfer (Irwin Heat Transfer)
 Anthony F. Mills
Inverse Heat Transfer Problems (International Series in Heat and Mass Transfer)
 Oleg M. Alifanov
Mathematical Modelling of Heat and Mass Transfer Processes (Mathematics and Its Applications (Kluwer Academic Pub), Vol 348
 V. G. Danilov, et al.
Momentum and Heat Transfer in Turbulent Gas–Solid Flows
 Z. R. Gorbis, F. E. Spokoyny
PC-Aided Numerical Heat Transfer and Convective Flow/Book and Disk
 Akira Nakayama
Principles of Heat Transfer in Porous Media (Mechanical Engineering Series)
 Kemal Hanjalic (Editor), J. F. C. Pereira
Turbulence, Heat and Mass Transfer 1
 Kemal Hanjalic (Editor), J. F. C. Pereira

2. Conduction

A variety of issues encompassing heat conduction are reviewed here and are sub-categorized as follows: contact conduction/contact resistance; layered/composite or anisotropic media and other effects; thermal waves, laser and pulse heating effects; heat conduction in geometries such as fins, tubes, solids; mathematical models, analytic/numerical techniques and simulations; experimental and/or comparative studies; thermo-mechanical interactions; inverse problems; conduction–convection and flow effects; solidification and change of phase; microelectronic heat transfer; materials processing and process modeling; and specialized and miscellaneous studies.

2.1. Contact conduction/contact resistance

Contact conduction of selected metal–matrix composites are described by Blanchard and Fletcher, Chung et al. [1A–4A] who studied the effect of surface deformations, thermal contact conductance of coated junctions and ceramic substrate junctions. Howard et al. [5A] investigated the effects of metallic vapor deposition on coating thickness on thermal contact conductance. Lambert and Fletcher and Lambert et al. [6A, 7A] investigated contact conduction in coatings. The thermal contact conductance under low applied load in vacuum environment is described by Nishino et al. [8A]. Other related work in this subcategory appears on constriction resistance in a finite heat flux tube [9A], and on the influence of surface preparation on the influence of thermal contact conductance of stainless steel and aluminium [10A].

2.2. Layered/composite and anisotropic media and other effects

Issues concerning microstructural influence on heat conduction [11A], effective conductivity of a macroscopically inhomogeneous disperation [12A], laminate delamination due to thermal gradients [13A], thermal tomographic detection of inhomogenities [14A], the cure behavior of dental composites [15A], variations in nanostructure and composition for controlling interfacial properties of metal matrix composites and ceramic matrix composites [16A], process simulation in thermoset composites for cure and stress predictions [17A], the heat transfer across a bilayer composite cylinder [19A], the tailoring of thermal deformation by using layered beams [20A], and constitutive models for anisotropic frictional heat [21A] appear in this subcategory.

2.3. Thermal waves, laser and/or pulse heating

The hyperbolic heat conduction with reference to the second law of thermodynamics is described by Bai and Lavine [22A] and the heat wave phenomon in IC chips is studied by Xu and Guo [24A]. Krajnovich [23A] discusses the laser sputtering of highly oriented pyrolytic graphite.

2.4. Heat conduction in fins, tubes and solids

In the study of heat conduction in various geometries, a variety of issues were addressed. These include, the determination of temperature field in a cylindrical electrical conductor with annular section [25A], exact modeling of thermal diffusivities of solid objects [26A], transient studies in eccentrically hollow cylinders [27A, 28A], conjugate heat transfer of a finned tube and heat transfer augmentation employing longitudinal vortex generators [29A], one-dimensional fin assembly analysis with dehumidification [30A], studies of heat flow rate in symmetrical two-dimensional conduction problems [31A], analytical determination of thermal conductivity from dynamic experiments [32A], heat transfer and pressure drop numerical studies in multi-louvered fins [33A], convection and heat transfer of elliptic tubes [34A], flow instability and augmented heat transfer of fin arrays [35A], studies on optimum spines and fin arrays [36A, 37A], model equations for heating and cooling of bodies of various shapes [38A], and studies of analytical solution in hollow cylinders containing a well-stirred fluid with uniform sink [39A].

2.5. Mathematical models, analytic/numerical techniques

Modeling/analysis continues to be a subcategory where a wide variety of studies were conducted in heat transfer. In this subcategory, development of mathematical models, analytic techniques and numerical approaches seem to focus on improved accuracy of physical models, solutions and computer-aided engineering analysis. Finite element techniques were applied to a variety of problems in heat conduction and appear in [46A, 51A, 52A, 58A, 61A, 65A–67A, 69A]. The use of BEM, spectral element and/or coupled to other techniques appears for a variety of applications provided in [41A, 42A, 44A, 53A–56A, 59A, 60A]. Analytical techniques and miscellaneous numerical studies and simulations also appear for a wide variety of problems as described in [40A, 43A, 45A, 47A–50A, 57A, 62A–64A, 68A, 70A–73A].

2.6. Experimental and/or comparative studies

Efforts to conduct experiments and/or perform comparative numerical/analytic studies appear in this subcategory. In certain instances, comparisons are drawn with available experimental data. Bhattacharya et al. [74A] studied the role of thermoelectric heat transfer in the design of SMA actuators with comparative theoretical modeling and experiment. The investigation of local heat transfer in compact heat exchangers by holographic interferometry appears by Fehle et al. [75A]. Grager and Rath [76A] described the measurement of the thermal conductivity of fluids with low viscosity under reduced gravity conditions using the transient hot-wire techniques and Gueldener et al. [77A] described the cooling of extruder strands via experiments and modeling. A function estimation in predicting temperature dependent thermal conductivity without internal measurements appears by Huang et al. [78A]. Mitra et al. [79A] describe experimental evidence of the phenomenon of hyperbolic heat conduction in processed meat. Other works appear on an augmented Young–Lapace model of an evaporating meniscus in a microchannel with high heat flux [80A], computational and experimental studies of laser-induced thermal ignition in premixed ethylene-oxider mixtures [81A], and the influence of heat conduction on determination of heat transfer coefficient by liquid crystal thermography [82A].

2.7. Thermal and thermo-mechanical problems

The problem of orthotropic thermo-elasticity of an antisymmetrical heat flow disturbed by three coplanar cracks is addressed [83A]. Dhaliwal et al. [84A] investigated small time Green's function in temperature rate-dependent thermoelasticity. The analysis of thermal stress in a plate of functionally graded material is described by [85A]. Klonz et al. [86A] measured thermoelectric effects in thermal converters with a fast reversed DC. A problem relevant to coupled quasi-stationary model of thermodiffusion for an elastic cylinder is described by [87A]. The problem of thermo-mechanical contact using numerical modeling is described by [88A].

2.8. Inverse problems, analysis and design studies

In this subcategory, inverse problems and variants thereof are reviewed. Archaumbault and Azim [89A] described the inverse resolution of the heat-transfer equation with application to steel and aluminium alloy quenching. Dulikravich and Martin [90A] describe geometrical inverse problems in three-dimensional nonlinear steady heat conduction. The application to the inverse determination of thermal conductivity for one-dimensional problems is studied by [91A] and a genetic algorithum for the solution of inverse heat conduction problems is addressed buy [92A]. Other studies included inverse analysis of linear temperature dependent thermal conductivity in orthotropic medium [93A]. the Kalman smoothing technique applied to the inverse heat conduction problem [94A] and inverse finite element application to roll cooling in hot rolling of steels and a two-dimensional heat conduction problem [95A].

2.9. Flow effects, change of phase and process studies

The effects due to convection in a variety of applications (forced convection or free convection) is described in [96A–101A, 103A–105A]. McAdie et al. [102A] describe finite element enthalpy techniques for coupled nonlinear heat conduction/mass diffusion problems involving change of phase. Spall [106A] describes spectral collocation methods for one-dimensional phase-change problems, and Udaykumar and Shyy [107A] discuss simulation of interfacial instabilities during solidification.

2.10. Microelectronic heat transfer

The problem of thermal performance of a pin-fin assembly is studied by Babus'Hag et al. [108A] and heat generation and transport in submicron semi-conductor devices is investigated by Fushinobu et al. [109A]. Goodson et al. [110A] describe studies of the prediction and measurement of temperature fields in silicon-on-insulator electronic circuits. Employing a local heating method, the performance evaluation of pin-fin heat sinks is addressed by Minakami et al. [111A]. An efficient computer-aided design of GaAs and InP millimeter wave transferred electron devices is addressed by Zybura et al. [112A].

2.11. Materials processing, special applications and miscellaneous studies

Lin and Chen [134A] and Lin and Yang [135A] studied rolling process analysis for thermal and thermo-mechanical models in process modeling. The problem of intra and interchain thermal conduction in polymers is described by Nystem et al. [141A]. In process modeling, the effects of inserts on the injection molding process is addressed by Rezayat and Jantzen [145A] and modeling the cure of gelcoat film on unsaturated polyester appears by Sahli et al. [147A]. Other special applications and miscellaneous studies in heat conduction are described in [113A–133A, 136A–140A, 142A–144A, 146A, 148A–156A].

3. Boundary layers and external flows

The papers on boundary layers and external flows during 1995 have been categorized as follows: flows influenced externally, flows with special geometric effects, compressible and high-speed flows, analysis and modeling techniques, unsteady flow effects, flows with films and interfacial effects, flows with special fluid types and property effects, and flows with combustion or reaction.

3.1. External effects

Papers which focus on external effects document the influence of magnetic turbulence [1B], the influence of induction heating [2B], and blowing and suction [3B, 4B].

3.2. Geometry

One category of papers in this section deal with cylinders in cross flow [7B, 10B, 12B, 16B]. Numerical solutions were presented for a cone in viscous flow [8B], oblate spheroids and non-spherical droplets [11B], and turbomachine airfoils [17B]. A series of papers showed surface geometry effects such as a concave wall [24B], a wavy wall [21B], flat plate arrays aligned at angles to the flow [22B], and a sieve tray [23B]. Many investigated surfaces with attached elements such as roughness elements [13B], a smooth strip on a rough wall [9B], protruding heater elements [19B], and simulations of electronic modules [6B, 15B, 20B]. Papers with variations in global flow geometry include one of buoyancy-induced flow in a box [5B], a casting flow [14B], and counter-flowing streams [18B].

3.3. Compressibility and high-speed flow effects

Modeling papers on this topic include one with an asymptotic two-layer model [28B], the development of a law of the wall [41B], shock/boundary layer interactions [26B, 27B] and transition to turbulence [36B]. Flows with geometric consideration included flows over a wedge or cone [35B], an airfoil [38B], a swept wing [25B] and a swept cylinder [40B]. One paper showed how mass addition could simulate heat addition in compressible flow [29B]. Computational papers included a Navier–Stokes computation in hypersonic flows [30B], a similarity solution [32B], an interactive inviscid/boundary layer method [39B] and a heat transfer coefficient evaluation [31B]. Compressible flows which focus on non-equilibrium effects include one with effects of boundary layer heating [33B], of dissociated fluid [34B] and hypersonic flow with catalytic walls [37B].

3.4. Analysis and modeling

Papers with primary focus on analysis and modeling include a self-similarity study [42B], an analysis of swirl flows [44B], the presentation of a perturbed boundary layer problem method [43B], a Monte Carlo application for 3-D flows [46B], and heat transfer with Lagrangian methods [48B]. Adaptive grid techniques were applied to a moving boundary problem [51B]. Coherent turbulent analysis was applied in one paper [45B] and an enthalpy balancing scheme in another [49B]. Applied studies included one of a passive nuclear containment [50B] and another in mixed convection [47B].

3.5. Unsteady effects

Presentations in the literature on unsteady effects include an unsteady boundary layer solution [55B] and boundary layer control by heat transfer [57B] and by suction [65B]. Unsteady flow included an impulsively started plate [54B], a suddenly stopped or cooled plate [58B], translating or spinning bodies [64B], an oscillating sphere [61B], oscillating smooth or stranded cylinders [67B], a pulsating stagnation flow [63B] and oscillating thermocapillary convection [66B]. Application papers include one of an internal combustion engine [53B] and a mass transfer probe [62B]. A paper was presented for the determination of intermittency for characterization of boundary layer change of state [60B]. Papers on processes included one on irradiation of a human eye [52B], crack propagation in the earth [56B] and a differentially heated cavity [59B].

3.6. Films and interfacial effects

Papers associated with films include deposition of films [70B], instability of falling films [68B] and free-surface films [69B].

3.7. Effect of fluid type or fluid properties

Papers which deal with specific types of fluids include one on alternative heat transfer fluids [72B] and one on micropolar fluids [74B]. Several dealt with particles, including one which documented enhancement of heat transfer on the bottom of a flume [75B], others on suspensions [78B] and sediments [77B], and one on volcanic flows [76B]. Finally, papers were presented on vaporizing flows [71B] and the propagation of metal/water explosions [73B].

3.8. Flows with combustion and reaction

Papers in this category included one on a laminar diffusion flame [80B] and another on a separation column [83B]. Fire studies include one over a mountain ridge [82B] and another in a compartment [79B]. Finally, a paper presented a mathematical model for use in fuel cell simulations [81B].

4. Channel flows

The literature contained in the broad area of wall-bounded flows was divided into the following subcategories: straight-walled ducts; irregular geometries; finned and profiled ducts; ducts experiencing secondary motion caused either by curvature, rotation or imposed swirl; pulsatile or oscillatory flow; two-phase flow in ducts (also see separate section on two-phase flow); non-Newtonian flow; and miscellaneous duct flows.

4.1. Straight-walled ducts

Ducts having straight walls but with arbitrary cross sections are reviewed in this subcategory. Mixed convection was considered in a number of studies including: the heating of liquids in isothermal ducts [24C]; laminar mixed convection [29C] and three-dimensional buoyancy effects [7C] in inclined rectangular ducts; vortex flow and thermal characteristics [13C] and fully developed flow [26C] in horizontal rectangular ducts; velocity–temperature correlations were examined in a strongly heated channel flow [27C]; and thermal instabilities were studied under mixed convection [1C]. Conjugate heat transfer was investigated in turbulent pipe flows [4C, 17C] and in a turbulent channel [30C]. Channel flows dominated by natural convection were also considered [3C, 14C]; an analytical solution for transient laminar conditions was also found in the literature [2C]. Computational studies included: integral transform methods [20C]; direct numerical simulation of turbulent channel flow [19C]; analysis of deterioration phenomena in heat transfer to supercritical water [15C]; a computational efficiency problem for thick-walled composite tubes [16C] and in rectangular ducts with mineral oil [10C]. Heat transfer was studied in an insulated exhaust pipe

[23C], at the inner region of smooth pipes and open channels [22C] and in packed ducts [11C]. Dual studies of heat transfer and pressure drop were conducted with large heat flux [9C] and using a two-parameter variational method [12C]. Magnetohydrodynamics and heat transfer was examined [6C, 25C] as well as the thermal aspect of the flow of liquid metals [21C]. Effects of streamwise radius of convergence on laminar forced convection was studied [18C]. Duct flows experiencing boundary conditions of the third kind [28C] and laminar–turbulent transition was considered using thermocouples [8C]. Finally, a spreadsheet solution for heat loss was given for flow in pipes [5C].

4.2. Irregular geometries

Complex passages are perhaps the most ubiquitious of all practical channel flows and are the focus of this subsection. A review was conducted of computational efforts at modeling internal gas-turbine cooling [39C]; turbine blade cooling was also examined using Chimera grids [49C]. Periodic or wavy channels were investigated by several research groups including: heat transfer in the presence of periodic transverse grooves [41C]; wavy channels with Taylor–Görtler vortices [38C] and with self-sustained oscillations [52C]; and in serpentine channels [33C]. The thermal convection patterns in a street canyon were studied [31C]. Flows in ducts of arbitrary cross section were considered [47C, 53C] as well as bundle geometries [32C] and in the cooling of optical fibers [50C]. Channels experiencing sudded expansions or slots were investigated, including: the magnetic field effect on heat transfer in a slotted channel [36C]; the slot flow between two vertical plates [46C]; thermomechanical problems associated with white-beam slits [44C, 45C, 48C]; and in sudded expansions [34C, 37C]. The effect of eccentricity in an annular duct was examined [42C], forced-convective cooling in a horizontal equilateral-triangular duct [40C], for fully developed flow in semi-elliptical ducts [51C] and the transient heat transfer in a concentric annuli [35C]. Experimental and numerical analysis of channels with square and circular columns [54C] and for a capillary looped pipe [43C] conclude papers in this subcategory.

4.3. Finned and profiled ducts

Ducts employing surface enhancements are the attention of this subcategory. So-called 'ribbed' ducts and the associated heat transfer augmentation and pressure drop were considered in the following studies: permeable ribs were examined in a rectangular channel [63C]; effects of clearance ratio and Reynolds number were studied [69C]; detached ribs were investigated using holographic interferometry [68C]; turbulent flow was calculated in a periodically-ribbed channel [60C]; experiments were conducted on the heat transfer and friction in a low-aspect-ratio channel [65C] and a numerical study was used to investigate ribbed channels with longitudinal vortex generators [73C]. Forced convective heat transfer was studied experimentally using ethylene glycol in tubes [67C]. A thermally-stratified channel flow with an obstruction was used to demonstrate the complex nature of species diffusion [59C]. Rib promoters as heat sources and their relevance to electronic packaging was considered in several studies [57C, 58C, 66C]. A vertical slab was used to examine conjugate heat transfer and secondary flow [56C], a built-in rectangular cylinder created heat transfer augmentation in a channel [72C], and normally in-line positioned plates were studied for periodically fully developed flow [55C]. Holographic interferometry was used to study the heat transfer in a rectangular channel with perforated turbulence promoters [64C]; surface enhancements were also used to study laminar natural convection [71C] and Prandtl number effects [70C]. Narrow channels having grooves were studied [62C] as well as two- and three-dimensional mixing devices [61C].

4.4. Duct flows with secondary motion

Secondary flow can lead to a variety of interesting fluid and thermal phenomena, including relaminarization as well as heat transfer augmentation and increased pressure drop. Secondary motion created by twisted-tape inserts in a rectangular duct was studied [79C] as well as the heat transfer enhancement and slow decay of swirl in tubes using tangential fluid injection [76C]. Local coefficients for forced convection in a curved duct, where secondary motion is established by centripetal acceleration, were studied in large aspect ratio rectangular channels [81C]. A numerical investigation of swirling reacting and non-reacting flow was accomplished using the Reynolds stress differential method [80C]. Embedded vortices were found to enhance both pressure drop and heat transfer rates [78C] and were used to validate computational methods [77C]. Secondary motion and heat transfer in curved passageways were studied using numerical methods [74C, 75C].

4.5. Oscillatory and pulsative flow

Flow periodicity can be imposed by boundary conditions or set up by flow instabilities leading to global changes in the thermal response of the system affected. Heat transfer was studied by oscillating flow in a circular pipe with a sinusoidal wall temperature distribution [85C]. A numerical solution of laminar forced convection was undertaken in a heated pipe subjected to a reciprocating flow [87C]. The effect of a thermally permeable wall on the enhanced longitudinal heat transfer by fluid pulsation in a pipe was investigated [84C]. The thermal-fluid effects caused by a dusty fluid were studied in an infinitely long annular pipe [83C] and unsteady forced convection was examined in a turbulent duct flow [86C]. Finally, an inverse problem utilizing the conjugate gradient method of minimization with adjoint problem was used to estimate the timewise variation of the inlet temperature of a thermally developing flow between parallel plates [82C].

4.6. Two-component duct flows

Air–water mixtures in an annular nonisothermal environment were modeled to characterize heat transfer and fluid flow [89C]. Critical heat flux was predicted in water-subcooled boiling [88C]. Coal–water mixtures were studied to determine the heat transfer coefficient under laminar flow conditions in a round tube [90C]. Physical and empirical models of heat transfer in two- and three-phase bubble column reactors were reviewed [91C]. The one-dimensional steady state conditions in stratified two-phase flow was modeled and compared to experiments [92C].

4.7. Non-Newtonian duct flow

The archival literature considering the behavior of non-Newtonian fluids may be the fastest growing segment within the broad category of duct flows. Heat transfer during resin transfer molding considered filling and cure cycle times [101C]; three-dimensional thin parts were modeled and analyzed numerically during compression molding [100]C. The flow structure within a periodically corrugated wall channel were studied experimentally for shear-thinning viscous fluids [94C]. Electronic models using non-Newtonian fluids were studied to demonstrate the combined effects of temperature dependence of viscosity, shear thinning and viscous dissipation [95C]. The conformal sliding contact between polymers and metals was studied subject to convective cooling [97C]. Power-law fluids were considered under the following conditions: variable viscosity and viscous dissipation effects in the entrance region of a semi-circular duct [96C]; combined convection flow in a vertical duct with linearly varying wall temperature [98C] and considering the extended Leveque solution in pipes with wall slip [105C]. The laminar cooling of pseudoplastic fluids flowing through a cylindrical horizontal pipe was considered [93C] as well as a numerical study of thermal convection for Herschel–Bulkley fluids [103C]. The heat transfer in a strongly magnetized ferrofluid was calculated in the case where there was strong heating from above [104C]. Nusselt number effects on viscous dissipation of non-Newtonian power-law fluids was considered [102C]; the heat transfer due to interfacial instabilities in plane Poiseuille flow of two stratified viscoelastic fluids was also found in the literature [99C].

4.8. Miscellaneous duct flows

Several studies of duct flows did not fit well into the subcategories identified above and appear in this subsection. Temperature profiles of a cooled multitubular catalytic reactor influenced by interparticle and intraparticle transport was reported [106C]. The heat transfer from flames positioned between vertical walls was studied to evaluate the risks associated with bulk storage of materials [109C]. The design process associated with heat tracing was described for a non-conducting pipe [107C]; a design chart was also developed for high temperature superconducting gas cooled current leads [111C]. HVAC system design was considered for process ventilation and temperature and humidity control [108C]. Wall-to-tube heat transfer was studied in a Kenics-type static mixer; uniform correlations were presented [110C]. A numerical model was developed capable of predicting the performance of a wave-rotor of specified geometry over a wide range of operating conditions [112C]. The heat transfer process of catalytic materials in a shock tube was modeled [113C].

5. Flow with separated regions

Rapid changes in geometry or large pressure gradients can lead to flow separation and concomitant changes in the heat transfer on nearby surfaces. The entrance region of an in-line array of rectangular blocks were used to correlate heat transfer and wake characteristics for simulating electronic components [13D]. Longitudinal flux indicators commonly used for induction heating were systematically studied [17D, 18D]. Flow past hot and cold circular cylinders was examined in a uniform air stream; correlations were developed to cover a wide range of temperature ratios [10D]. Three-dimensional particle tracking measurements were used to determine the energy budget in a backward-facing step flow [11D]. A nominally two-dimensional turbulent flow at high Reynolds numbers experiencing separation and reattachment was studied in the near-wall region [12D]; upstream effects of wall heating were also investigated [1D]. A tube array subjected to a gas–particle flow was considered and impact on Nusselt number was presented [19D]. The flow around a droplet and the associated evaporation was studied [5D] as well as the flame stabilization and flowoff over a single droplet [6D]. The unsteady separation and heat transfer upstream of an obstacle was considered in the presence of a laminar boundary layer [14D]. Hypersonic separated flows were examined [9D, 15D] as well as compressible turbulent flow in a laser cavity [20D]. The effect of heat transfer on snow loads was investigated in four Canadian cities [8D]. A numerical study addressed laminar and turbulent flow and heat transfer in tube banks [21D]. The convective heat transfer coefficients between a spherical particle and a fluid at lower Reynolds numbers was calculated [7D]. Numerical studies included: coupled fluid and heat transfer using unstructured moving meshes [4D]; using streamfunction–vorticity based finite-element formulations for laminar convection [3D]; and for a motorized engine utilizing a two-boundary method-grid generation technique [2D]. Finally, the Romelt process was examined for iron smelting [16D].

6. Heat transfer in porous media

The literature on heat and mass transfer in porous media continues to expand in both fundamental and applied directions. The literature also appears to be segregating itself in broadly defined areas that include properties determination, free (or natural) convection, mixed convection, forced convection, mass transfer, coupled heat and mass transfer, multiphase flow and heat transfer, and reacting systems. For some years, the last category has formed the bulk of the engineering science literature in the field owing to the universal applicability of packed bed reactors in the chemical process industry. As applications of packed beds have widened, more in-depth knowledge of both properties and transport processes have become necessary, and this has also driven the expansion of the literature.

With the foregoing, the very fundamental underpinnings of transport in porous media have continued to generate several important papers each year. For 1995 such studies have addressed momentum transfer via both experiments and theory [2DP, 3DP], the limitations of the Brinkman–Forcheimer-extended Darcy equation [6DP], mechanisms of liquid retention and evaporation in two-phase thermocapillary flow [4DP, 5DP] and the diffusion-reaction problem in a bed of irregularly shaped particles [1DP].

6.1. Thermophysical properties

Both theoretical and experimental work continues to expand on the determination of the thermophysical properties of a porous material saturated with either a liquid or a gas. The focus of all recent studies reviewed has been on the 'effective' values to be used while a particular transport process is realized. For example, the effective permeability of layered media has received attention [10DP] via a theoretical treatment, and a model of the moisture capacity as a function of pressure has been proposed [13D].

By far, the determination of the effective thermal conductivity of a saturated medium has received the most attention during 1995. Zeng et al. [14DP] have performed calculations on the mean free path and effective thermal conductivity in a porous medium. Fundamental experiments have been carried out on solid-liquid phase transitions in saturated media [9DP]. Effective thermal conductivity in light of the geometry, or structure, of the porous matrix has dealt with scaling rules based on cavity shape [12DP], as well as macro-modeling based on the overall internal structure [7DP, 8DP, 11DP, 15DP].

6.2. Free and mixed convection

Several aspects of free and mixed convection in saturated porous media have received attention, mostly via theoretical and numerical studies. The onset of buoyancy induced flows with time-dependent volumetric heating and with mixed thermal boundary conditions in a horizontal layer were investigated theoretically [36DP, 45DP], as were transient flows with conjugate boundary conditions, a temperature-dependent viscosity, and a density extremum [21DP, 41DP, 44DP]. Theoretical work on free convection in fissured systems were also published and indicate that the convective component of heat transport needs to be taken into account in an otherwise non-fractured matrix [16DP, 24DP]. Flows from vertical surface embedded in a saturated medium also received attention [29DP, 39DP]. An interesting applied study in which flow and heat transfer in a molten soil induced by an electromagnet field generated by a thermal plasma was reported [37DP].

Mixed convection in a partially filled cavity [20DP] and in a square channel [23DP] were investigated numerically. The latter study considered the effects of stagnant thermal conductivity and non-Darcy effects. The influence of surface mass flux on the vortex mode of instability has been carried out [30DP], and nonsimilar solutions for wedge flows in a porous medium have been presented for several wedge angles [43DP].

Although a well studied area, fully developed flow in layers and vertical cavities continues to receive attention. Numerical solutions for the effect of coriolis forces on flow in a porous box [42DP], Hadley circulation induced by inclined temperature gradients [32DP], convection in layers with solid conductive inclusions [31DP], convection induced by sources in semi-infinite layers [26DP, 28DP], and flows in filled and partially filled cavities [34DP, 35DP, 38DP] were published. One study has tackled the difficult problem where both the fluid and the porous matrix are anisotropic [25DP].

Research on buoyancy driven flows in vertical cavities has examined the effects of mass transfer and structure of the wall boundary [22DP, 40DP]. The basic annulus problem continues to be addressed for a variety of thermal boundary conditions and for transient and steady state flows [17DP–19DP, 27DP, 33DP].

6.3. Forced convection

Forced convection in porous channels and annuli is of high continuing interest owing to a multiplicity of industrial heat transfer applications. Several very fundamental studies have appeared that treat specialized problems that emphasize various aspects of this area. These include finite difference solutions for viscous flow and heat transfer between two porous rotating disks [56DP], fluid flow analysis in an axially rotating porous pipe with mass injection at the wall [49D], heat from a surface covered by flexible fibers [50DP], and a two-temperature model for turbulent flow and heat transfer in a highly porous layer [58DP]. Transient compressible flows during either a pressurization or depressurization were subject to theoretical modeling [46DP, 55DP].

Forced flow with heat transfer in fractured rocks [54DP] was analyzed via a deterministic fracture flow model, and forced convection in partially filled channels with discrete heat sources and axisymmetric heating was numerically investigated [51DP–53DP, 57DP]. Non-Darcian flows were also of interest for channel flows [47B, 48B].

6.4. Packed and fluidized beds

Heat transfer in forced flow in packed beds was investigated both with and without imbedded heat transfer tubes. Effective heat transfer coefficients in such beds are of great interest, and a Bayesian estimation framework for data from ill-controlled experiments was presented [63DP]. Experimental data were reported on general heat and flow characteristics under conditions where radiant heat transfer may be neglected [60DP] and for a liquid-solid bed [65DP]. A steady-state thermal-hydraulic model of heat transfer was developed for pebble bed blankets for fusion reactors [78DP]. A two-dimensional model for a stationery packed bed was developed taking into account void and velocity distributions [67DP]. Local instantaneous and time-averaged heat transfer in a pressurized fluidized bed with horizontal tubes was investigated theoretically to determine the influence of pressure, fluidization velocity and tube-bank geometry [73DP]. Local particle heat transfer along surfaces [64DP] and non-Darcy convection with anisotropic dispersion [61DP, 62DP] received theoretical attention. The development of a mechanically fluidized bed vacuum furnace apparatus was also reported [59DP].

Enhancement of heat transfer in a fluid bed via direct contact heat exchange was studied experimentally using an optical visualization technique [66DP]. Local heat transfer rates, solids concentration and erosion around membrane tubes in a cold model circulating fluid bed were also reported [68DP]. Steady and transient numerical results were presented for a circular cylinder embedded in a porous medium in steady viscous flow [72DP, 74DP, 75DP]. Unsteady heat transfer and particle behavior around a tube bundle in a gas fluidized bed was measured [69DP]. This study also presented interesting data on particle packing in the vicinity of the tube bundle.

Research on several important aspects of fluidized bed dynamics have received attention as well. A model to predict heat transfer in the grid region in a shallow gas–solid bed was developed [76DP]. Particle migration near solid surfaces in bubbling fluidized beds received both experimental and theoretical attention [70DP, 71DP]. A model for wall to suspension heat transfer rates in circulating fluid beds was developed [77DP].

6.5. Multiphase transport

Multiphase transport processes in both fixed-matrix and fluidized bed porous media have received limited attention during the past year. Local particle heat transfer in three-phase fluidized beds was investigated experimentally using the conductivity technique [80DP]. Thermal dispersion effects on condensation in forced convection in a unique porous/fluid composite system were modeled via a local volume averaging technique [82DP]. Experimental data on solidification within a rectangular porous region in which the matrix represents the solid phase were reported [81DP] and a transient analysis was performed of the start up of a water heat pipe from the frozen state [84DP]. A model for coupled water flow, air flow and heat transfer in a deformable porous medium was developed [83DP]. Mass transfer of free convection in an electrically conducting visco-elastic fluid in a porous channel effects were analyzed [79DP].

6.6. Coupled heat and mass transfer

Coupled heat and mass transfer has received attention from both the fundamental and applied perspectives. Fundamental studies have addressed various aspects of a general model for evaporation [90DP, 97DP], dispersion effects [100DP], structural effects on adsorption-desorption processes [89DP, 93DP] and integral modeling [102DP]. Some investigations are also ongoing for generally well studied problems. These include the effects of oscillatory flows over porous surfaces [91DP] and double diffusive convection in enclosed systems [99DP].

Heat and mass transfer in packed beds of various kinds continues to receive considerable attention. Metal hydride beds have received theoretical attention [88DP, 92DP]. Adiabatic gas adsorption in packed columns with large thermal effects was investigated experimentally [106DP], and readsorption in a sorption bed heat exchanger during pressurization and depressurization was measured [108DP]. An analysis of transient heat and mass transfer data for heterogenous catalysts was presented to elucidate the extra- and intraparticle effects [86DP]. The aerodynamics and heat transfer during the coating of tablets in a two-dimensional spouted bed were experimentally investigated [103DP].

From an applications viewpoint, coupled heat and mass transfer in porous systems remains of high interest in various drying processes and for a variety of applications for fluid beds. Experiments have been reported for the Lurgi Circofer and Circored processes [85DP], and the application of fluidized beds to power coating technology has been reported [94DP]. Experiments on the drying of wood products [105DP], transport of heat and vapor in soils [107DP], and the curing of concrete structures [87DP, 95DP, 96DP, 98DP, 101DP, 104DP].

6.7. Reacting systems

Packed beds, fixed porous materials, and fluidized beds have been used as the basis for reacting systems in a variety of process technologies. Reacting systems as such involve all of the topical areas reviewed above, as well as chemical kinetics.

Fundamental studies of transport effects in falling film flow inside a porous medium [129DP] oxidation reactors [123DP], multi-step reaction and gas evolution in a porous compact [125DP], and mass transport accompanied by chemical reaction using the Fick model and dusty-gas model [126DP] were reported. Specialized, though very fundamental studies were directed at the convective instability induced by differential transport in a tubular packed-bed reactor [128DP], the prediction of transport and kinetics in packed bed enzyme reactors [120DP], shrinkage and activation of highly porous chars during combustion in an electrodynamic chamber [127DP] and modeling the burnout of the organic binder in green dense ceramic compacts [114DP]. Heat and mass transfer in multistage polymerization processes were analyzed for a loop-fluidized bed process [111DP]. Reaction kinetics of metal hydride reactors received attention, and the effective value of the thermal conductivity used in the theoretical model was seen to play a role in certain regimes of transport [118DP, 119DP]. The production of microcellular ceramic foams were investigated via a series of nicely coordinated physical experiments and finite-difference models [115DP]. A general analysis of the effects of varying operating parameters on the stability of packed bed, gas-phase polyethylene reactors [122DP].

Work on combustion systems dealt with a variety of practical problems and several articles presenting overviews of the field were published [109DP, 110DP, 117DP]. Unsteady flame spread and burning processes [112DP] and superadiabatic combustion of methane-air mixtures under a ‘filtration’ flow mode [130DP] were investigated experimentally and theoretically. The study of slowly combusting systems included modeling the propagation and extinction of forced opposed flow smolder waves with the oxidation of the porous matrix [124DP], wind-opposed flame spreading in a charring solid in a microgravity environment [113DP]. Pyrolitic processes were also of some interest, being motivated in part by solid waste disposal [116DP, 121DP].

7. Experimental techniques and instrumentation

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

7.1. Heat flux measurements

Surface heat flux is often measured by a heat flux transducer or calorimeter. The principle of a zero-balance heat flux meter is described [7E] and fast time response in-situ calibration using a shock tunnel is developed [4E]. Two papers discuss the application of a quasi-adiabatic calorimeter to measure heat flux rates in a fusion environment [5E, 6E]. Heat flux measurements in IR radiative environments [1E, 2E] and tracking of turbulent spots [3E] were reported.

7.2. Temperature measurements

Innovative uses of traditional temperature sensors such as thermocouples [17E, 19E, 20E] and thermistors [15E] have been presented. Various surface temperature measurement methods have been developed including infrared thermometry [11E, 21E, 32E], liquid crystals [8E, 10E, 31E] and temperature sensitive fluorescent paint [14E, 25E, 26E, 30E]. Laser speckle photography [18E, 24E, 27E] and interferometry [12E] have been used to determine temperature fields in gases and liquids.

Additional work on noninvasive methods has been done to investigate laser beam displacement in highly turbulent flow [13E] and to measure 3-D temperature fields in the human body using microwave radiometry [28E]. The effect of temperature variation in high precision measurements [23E] and several novel applications of temperature measurement have been reported [9E, 16E, 22E, 29E].

7.3. Velocity measurements

Several papers discuss design features and operational improvements of hot wire anemometers [33E, 34E, 36E, 40E, 41E]. A new ultrasonic velocity measurement device was described [39E] and an autocorrelation algorithm for LDV data was presented [38E]. Several methods for measuring mass flow rates were introduced [35E, 37E, 42E].

7.4. Property measurements

Thermal conductivity measurements have been performed in gases [54E], refrigerants [53E], bone tissue [58E] and bulk materials [52E]. Measurement methods have been developed to determine the thermal diffusivity of solid materials [60E] and shapes that approximate fruits and vegetables [43E–49E]. Heat transfer associated with diffusion coefficient measurements in metal alloys has been addressed [51E, 59E]. Thermal resistance values have been measured for carbon–carbon composite materials [50E], building insulation [56E, 57E] and clothing [55E].

7.5. Heat transfer coefficient measurements

A method utilizing a combination of surface temperature and a composite slab was given to determine the heat transfer coefficient on a flat plate [64E]. Coefficients from 3-D solid objects were determined to simulate fruits and vegetables [61E–63E]. Measurement of local heat and mass transfer coefficients using a swollen polymer and interference fringes was described [65E].

7.6. Miscellaneous methods

Measurement methods that do not fit any of the categories above are included here. These included measurements of droplets or bubbles in two-phase flow [68E, 72E], bidirectional reflectivity [67E], effect of response time [69E, 70E], optimal sensor location [66E] and the use of platinum thin films [71E].

8. Natural convection—internal flows

The literature on natural convection has contributed some very useful results for otherwise standard geometries but with the added feature of three-dimensionality in the flow, complex boundary conditions, and coupled heat and mass transfer.

8.1. Stability of layer and cavity flows

There was renewed interest in the stability of buoyancy driven flows in layers and cavities, both from the perspective of the onset of flow and the bifurcation of flows. Enclosures of simple geometry have been the focus of most studies [1F, 2F], as well as linear stability under non-Boussinesq conditions [3F].

8.2. Enclosures

Buoyancy driven flow in all types of simple enclosures continue to receive the attention of researchers in both heat transfer and fluid mechanics. The power of modern computers however has enabled simulation of complex flows to such a degree that reports of fully numerically obtained results dominate the literature. Perhaps this represents the research paradigm for the foreseeable future, at least for simple enclosures, such as layers of moderate aspect ratio, and two-dimensional systems with regular geometric cross sections [9F–11F, 15F, 18F, 19F, 21F, 22F, 30F]. Some interesting data obtained by [33F] on Rayleigh–Benard flow in a rectangular enclosure report temperature and velocity fields. The inverse problem, i.e., the problem of predicting a cavity shape in which natural convection exists, continues to receive attention [16F, 23F, 25F].

A large number of studies have been reported wherein both complex thermal and shear conditions on one or more of the boundaries of the enclosure drive the flow. Typical boundary effects include discrete heating, periodic heating, open surfaces, and moving boundaries [7F, 8F, 12F–14F, 17F, 24F, 26F, 28F, 29F, 31F, 32F]. Khallouf et al. [20F] have investigated cavity flows in which there is transverse vibration and a longitudinal temperature gradient and Or and Kelly [27F] and investigated the onset of Marangoni convection driven by oscillatory shear at one boundary.

Some very fundamental studies, such as that by Abib and Jaluria [4F] address processes that occur in fires and other industrially important situations where the enclosure geometry is a major element in the thermo- and fluid dynamics. Magnetic field effects on enclosure flows were investigated by Alchaar et al. [5F, 6F].

8.3. Vertical cavities and slots

Vertical cavities and open slots received attention from a number of fundamental and applied aspects. Free convection in multiple vertical slots [35F, 36F], buoyancy dominated flow in rock fractures [39F], transient flows [38F], combined mode heat transfer [34F], and penetrative thermal convection [37F] were the primary areas of investigation.

8.4. Complex cavity geometries

Industrially important problems in which natural convection dominates were a major focus of analysts and experimenters alike. Variations of the simple enclosure problems reviewed above have been generally motivated by specific technology applications, such as nuclear reactor heat transfer [45F], flow in closed loops [53F] and cooling of electronic equipment. More fundamental studies generally treat either cavities of simple overall shape with protrusions introduced on the boundaries [43F, 50F, 52F, 55F, 57F] or cavities of simple shape in which another object is placed, such as a permeable barrier or a vent [40F–42F, 47F–49F, 56F].

There also continues to be much work on buoyancy dominated flow in structures that are typically found in buildings [44F, 46F, 51F, 54F, 58F].

8.5. *Coupled heat and mass transfer*

Coupled heat and mass transfer has been investigated in several contexts. The fundamentals of solution transport in enclosures [60F], the dynamics of species and temperature fields in steel-slag systems [59F], and transport in double diffusive layers [61F] were reported.

8.6. *External natural convection*

Several rather classical and well worked problems have received some attention in the 1995 literature. Combined heat and mass transfer in laminar flow from a vertical plate in a double diffusive system was investigated via similarity methods [64F], and a new methodology [65F] introduced the so-called 'average magnitude analysis' for both external and cavity problems. Buoyant plumes also received some attention, and reported research continues to provide valuable details of velocity and concentration fields in turbulent plumes that are encountered in combustion systems [62F, 63F].

8.7. *Thermocapillary convection*

Thermocapilliary convection continues to receive interest from a variety of aspects, both fundamental and applied. Nishio et al. [71F] have reported interesting results on oscillatory flow enhanced by a capillary bundle connecting two thermal reservoirs, and Peltier et al. [72F] investigated time-dependent flow in layered fluid systems. Work on cavity-type systems is beginning to appear, such as are encountered in materials processing [66F, 70F]. Hydrodynamic stability and the effects of gravity on the rewetting of capilliary groove surfaces [67F, 68F], and multiple transport mechanisms also received some attention [69F].

8.8. *Fires*

Relatively few articles from the rather large literature on fires have apparently addressed fundamental heat transfer issues. Scaling studies of fire extinguishment [74F], the spreading and dilution of dense cold clouds [76F], and smoke movement under a ceiling [73F] received attention with both experiments and analysis. A contribution to the theory of flashover was made by [75F] via an analytical study.

9. Natural convection—external flows

9.1. *Vertical flat plate*

Studies on natural convection heat transfer from a vertical plate include measurements of the temperature field and visualization of the flow for step changes in the heat flux boundary condition with some of the studies considering periodic changes on the vertical wall [3FF–5FF]. Another study considers flow over a backward facing step on vertical wall with constant wall temperature boundary condition [1FF]. A related mass transfer study examines convection on a vertical wall under unsteady electrolysis of an electrochemical solution [2FF]. A numerical study [6FF] predicts average Nusselt and Sherwood numbers on a vertical surface with combined heat and mass transfer natural convection in a binary mixture. A schlieren technique indicates the thermal field and heat transfer characteristics of a system of two staggered vertical plates surrounded by air [7FF].

9.2. *Horizontal plates*

Use of a wide range of test plate sizes permitted experiments over a large range of Rayleigh numbers for heat transfer by natural convection from an upper facing horizontal plate [9FF]. The onset and development of flow above a suddenly heated horizontal surface includes a range of flow structures from the conduction regime, to the onset of flow, to turbulent-type flow [8FF]. Corona wind from a high voltage wire enhances natural convection heat transfer from a horizontal flat plate [10FF]. Combined heat and mass transfer from horizontal and inclined plates with variable surface temperature and concentration have been described numerically [11FF].

9.3. *Cylinders*

A study on natural convection from cylinders includes measurements of the temperature distribution on inclined, slender cylinders immersed in air or water over a range of Rayleigh numbers [12FF]. A numerical study [14FF] describes the convection from enclosed horizontal rod bundles. Optimization of the spacing between horizontal cylinders to obtain maximum convection has been examined numerically and experimentally [13FF]. Natural convection mass transfer from a vertical array of horizontal cylinders has been studied in an electrochemical system with a copper sulfate solution [15FF]. A combined numerical, analytical and experimental study indicates maximum heat transfer from vertical and horizontal cylinders with square wave variations in the surface heat flux [16FF].

9.4. *Bodies of revolution*

A method of visualizing the natural convection heat transfer from a sphere using numerical prediction has been demonstrated [18FF]. Convection in power law fluids near a three-dimensional stagnation point has been predicted numerically [20FF]. An analytically based correlation for convection from rectangular heat sinks of various sizes and geometry has been compared to experimental data [19FF]. Convection around two interacting isothermal cubes has been studied using interferometry [17FF].

9.5. *Mixed convection*

Studies of mixed convection on vertical plates include consideration of temperature dependent properties [25FF] and the influence of spatially discontinuous surface heating [26FF]. Convection of a non-Newtonian fluid past a vertical wedge has been analyzed [27FF]. An asymptotic expansion indicates when steady flow can occur and what that flow will be with mixed convection over a horizontal plate [29FF]. The onset of longitudinal vortices above a horizontal surface with flow over it has been studied with a variety of experimental techniques [24FF]. Unsteady vortex rolls [23FF] and inflow when a micropolar fluid is present [22FF] have been studied for flow over a heated horizontal plate. A nonsimilar boundary layer analysis describes mixed convection in a non-Newtonian fluid around a vertical plate [30FF]. Different methods are used to evaluate the mixed convection about a rotating body of revolution [21FF]. A finite element technique has been applied to solve problems in mixed convection [28FF].

9.6. Miscellaneous

Studies related to convection that occurs in crystal growth systems have been used to provide simulation of the flow in float zone devices [31FF] and in the oscillatory flow modes in Czochralski convection [33FF]. Double diffusion natural convection in liquid metals has been studied with a numerical method [32FF]. An analytical approach and optical observations have been used to improve understanding of the influence of electric fields on natural convection [34FF]. The influence of sound on convection has been considered in low temperature systems [35FF].

10. Rotating surfaces

10.1. Rotating disks

A study of steam condensation on a rotating flat plate has been performed to evaluate the use of centrifugal force in condensers [1G]. Another experimental study investigated the effect of a channel on heat transfer from a rotating disk [3G]. Numerical solutions have been obtained for heat transfer from coaxial rotating disks [4G] and for radial throughflow between a stationary and rotating disk [2G].

10.2. Rotating channels

Most of the papers published on channel flows with rotation about or parallel to the axis were based on numerical solutions. Geometries include a rotating pipe [16G], rectangular ducts [17G], tubes with twisted tape inserts [15G] and elliptic ducts [5G]. Mixed convection through rotating vertical [11G] and horizontal [7G] annuli were studied. Investigations of channel flows in which the axis of rotation is perpendicular to the channel axis include the study of single and double pass ducts [8G, 9G]. Several investigators presented results of flows in channels with internal ribs or turbulators [10G, 13G, 14G, 18G]. The influence of Coriolis force on Hartmann flow was investigated numerically [12G]. Three-dimensional solutions were obtained for flow and heat transfer through four rows of turbine blades [6G].

10.3. Enclosures

Geometries considered in rotating enclosure flows include gas-filled horizontal circular annuli [19G] and a rotating square cylinder in a cylindrical enclosure [22G]. The effect of baffles on the flow in the melt region during crystal growth [20G] and heat transfer in a rotating tire [21G] were simulated.

10.4. Cylinders, spheres, bodies of revolution

Heat transfer from a rotating cylinder in crossflow [26G] and between a rotating cylinder and a granular bed [23G] were presented. Solutions were obtained for mixed convection from a rotating cone in a micropolar fluid [24G] and from a rotating cup-like cylinder [25G].

10.5. Journal bearings

Three numerical studies were published that considered heat transfer in oil lubricated journal bearings [27G, 28G, 30G]. A method to estimate power losses in magnetic journal bearings was presented that used temperature measurements and the solution to an inverse heat conduction problem [29G].

11. Combined heat and mass transfer

A number of somewhat disparate areas in heat and/or mass transfer are reviewed in this section. These include transpiration cooling, ablation, film cooling, jet impingement, spray and mist cooling, and drying systems.

11.1. Transpiration and ablation

A transpiration coolant passes through a porous surface to protect the surface from a hot gas stream flowing over it while ablation occurs when high heat flux to a solid surface produces loss (one hopes intentionally) of material by a number of processes including sublimation and chemical decomposition. One transpiration study [3H] at high mach number observed a reduction in heat transfer of 14%; another [6H] found a dissociating coolant improves transpiration cooling in stagnation region flow [5H].

A numerical model predicts the induced stresses in ablating composite materials [2H], while a second numerical study [8H] involves the modeling of ablation phenomena as two-phase Stefan problems. Experiments indicate the flow and radiation around an ablating flight model [4H] and ablation of aluminium fins [1H]. Ablation has been studied experimentally using tungsten films [9H] while an analysis includes the effects of mechanical stress [7H]. Transpiration cooling has been applied to mixed convection in a rotating duct [11H], while a reinforced-carbon ablating material has been used on shuttle orbiter flights [10H].

11.2. Film cooling

Film cooling in which a fluid is injected at discrete locations along a surface into the boundary layer to prevent overheating of a wall has been of particular interest in gas turbine applications, though it has wider uses as well. Recent studies include experiments on the effect of flow turbulence on film cooling effectiveness [13H], an analysis [14H] utilizing different turbulence models, numerical simulations [15H] and use of a mass transfer analogy to measure film cooling [16H]. Development of efficient grid systems for studying film cooling for gas turbine combusters has been described [18H] and the influence of counter-current wall jet injection on downstream flow and heat transfer has been examined [17H]. A review of the works on film cooling of the late Daryl E. Metsger has been presented by some of his past students and colleagues [12H].

11.3. Submerged jets

Impinging jets are used in a number of cooling applications including micro electronic systems, gas turbine blades and glass production. The thin boundary layer in the stagnation region provides high localized heat transfer while an array of jets can cool larger surfaces. Submerged jets are jets in which the fluid in the jet is similar to the fluid in the surroundings (e.g. air into air or liquid into similar liquid). In contrast, a free jet or free surface jet might be a liquid jet entering an ambient gas, where the density of the jet is considerably higher than that in the surrounding medium and surface tension effects may be important.

Studies on heat transfer to single impinging jets include measurements using laser-induced fluorescent thermal imaging [20H] and liquid crystals [30H]. Euler equations are solved to describe the flow field of an impinging jet at high Mach number [32H] while a computational technique [29H] has been applied to study heat transfer with radial jets. Experiments indicate the enhancement that can be found with impinging jets using a rod near the impingement surface [28H]. Studies in confined systems include experiments with an oblique impinging jet [27H] and a circular jet [31H], while turbulence models [26H] and large scale eddy simulation [24H] have been applied to determine local heat transfer. Studies with arrays of jets include the effects of non-uniform flow through different jets [36H] and of confining surfaces [35H]. Other studies consider heat transfer from a 3-D turbulent wall jet [19H] and from the region downstream of a backward facing step through which a jet emerges [34H], thermophoresis effects in three-dimensional reacting jet flow [37H, 38H], an impinging Mach 8 jet [23H] and mixing of opposing heated line jets [22H]. Submerged liquid jet studies include liquid fluorocarbon jets from an experimental [21H, 25H] and numerical point of view [33H].

11.4. Liquid jets and spray cooling

Liquid jets going through a medium of much lower density (often air) have been used in a number of cooling applications. Experiments include the effects of turbulent dissipation in planar jets of water [50H, 51H], local heat transfer measurements using an infrared radiometer [47H], measurements on jets impinging on concave surfaces [42H], turbulent two phase jets [41H], and liquid spray cooling under the influence of very low gravity [43H] and at high temperatures [40H]. Experiments have been performed with spray cooling using liquid nitrogen [48H, 49H]. Analyses include thermocapillarity effects on break up of a jet [45H], heat transfer from diesel injection sprays [44H], water gas spray fire extinguishers [46H] and thermally sprayed polymer coatings [39H].

11.5. Miscellaneous

Use of the mass transfer analogy to study heat transfer has been presented in a review [57H], and applied to mass transfer from a flat plate [63H]. Studies on interaction of heat and mass transfer on wall boundaries [52H], and the use of a photographic method for imaging mass transfer in aqueous solutions [54H] have been described. Additional studies on heat and mass transfer include non-isothermal effects in catalyst particles [61H], simultaneous heat and mass transfer with chemical reaction [55H, 56H], polymerization of olefins [62H], the sublimation growth of SiC crystals [58H] and measurements in crushed oil shales [53H]. Other studies include analyses of heat and mass transfer in stirred tank reactors [65H], distillation and reflux systems [60H], frost formation on a vertical cylinder [64H], and blankets in fusion reactors [59H].

12. Change of phase—boiling

Thermal transport phenomena associated with liquid-to-vapor phase change are addressed in the publications reviewed in this section and classified into four major categories: droplet and film evaporation (23 papers), bubble characteristics and boiling incipience (10 papers), pool boiling (38) and flow boiling (50). In addition to these 122 papers, dealing with evaporative and ebullient heat transfer, the interested reader will find these phenomena addressed in some of the papers included in the following sections: change of phase—condensation (JJ), heat transfer applications—heat pipes and heat exchangers (Q), and heat transfer applications—general (S).

12.1. Evaporation and droplets

The evaporation of droplets is of importance in understanding and predicting the behavior of combustion of liquid fuels, spray cooling and atmospheric aerosols. Models and predictions for evaporation from small isolated drops, which underpin many of the applications in this field, continue to enrich the literature. The 1995 archival literature contains several descriptions of fundamental studies of evaporation, including the behavior of a saline droplet in a uniform laminar flow [6J], a methyl alcohol droplet vaporizing in a turbulent round jet [1J], the influence of temperature dependent gaseous diffusion coefficients on the mass transfer rate from a water droplet in a flow field [13J], the effects of thermal diffusion and combustion product radiation to a large drop [7J], and of the simultaneous effects of interface vapor generation and noncontinuum behavior on heat transfer controlled microdroplet evaporation [4J]. Additional studies in this category provided experimental results for vaporization of a droplet impinging on a ceramic-coated surface [16J] and for the onset of EHD instability on the surface of a drop [15J], and numerical results for sublimation from a droplet exposed to an alternating magnetic field.

The issues encountered in evaporating sprays were explored by [12J], which provides an evaluation of droplet break-up models, by [19J] which analyses multiple arrays of droplets in a non-uniform, transient boundary layer flow, by [3J] which offers experimental mass transfer coefficients for dispersions, and by [5J] which presents the results of numerical studies of evaporating sprays in anisotropically turbulent flows. Heat transfer between a hot surface and an impinging spray was the subject of [2J, 8J, 11J].

Evaporation of thin liquid films falling along vertical walls was examined in [14J, 17J, 18J]; film evaporation in the presence of turbulent flows in a wetted channel and along an inclined, heated plate was the subject of [21J] and [20J], respectively; and the evaporation of falling films on horizontal tubes was discussed in [9J, 10J].

12.2. Bubble characteristics and boiling incipience

Studies of the formation, growth, and departure of vapor bubbles are essential to a greater understanding of ebullient heat transfer and two-phase flow. The prediction of vapor bubble growth rates attracted the attention of several authors, including Mei, Chen, and Klausner who performed a numerical analysis of bubble growth in saturated hetereogeneous boiling [25J], identified four dimensionless groupings that appeared to control this phenomena [26J], and developed a simplified analytical model for bubble growth rate [22J]. Exact analytical solutions for spherical symmetric bubble growth in an infinite medium of pure liquids and binary mixtures are presented in [28J]. Measurements of bubble detachment frequency and rise velocity in nucleate pool boiling of FC-72 from wires are reported in [27J] and departure frequency of coalesced bubbles on disks and wires is the subject of [24J]. The characteristics of bubbles growing and detaching from a vertical wall, with and without the influence of a flow field, are described in [31J] and the effect of the upstream contact angle on bubble removal in subcooled flow boiling in [23J].

Boiling inception in falling films of binary mixtures is experimentally studied in [30J]. Experimental results and a model for spontaneous vapor explosions generated by molten tin in water are reported in [29J].

12.3. Pool boiling

Archival publications in pool boiling reflect the continued interest in the fundamental aspects of ebullient heat transfer, along with a focus on electronic cooling, thermosyphon reboilers and a wide variety of augementation techniques. Fundamental studies of pool boiling heat transfer published during 1995, included the derivation of a new drift flux model to account for the void fraction present during pool boiling [33J], the determination of the properties of the nucleate boiling vapor stem [46J], the macrolayer thickness in saturated nucleate boiling [42J], the computational exploration of non-linearities in boiling behavior associated with transient three-dimensional conduction effects [57J], and the experimental investigation of pool boiling of binary mixtures [64J], as well as the effects of dissolved gas on pool boiling of highly-wetting liquids [68J] and the pool boiling of 3He [45J]. Significant attention was also devoted to pool boiling under reduced gravity conditions [32J, 54J, 61J] and pool boiling from arrays of discrete heat sources [35J, 41J].

The need for heat transfer enhancement in refrigeration, cryogenic and electronic cooling applications prompted studies of pool boiling on finned tubes [48J] and downward-facing curved surfaces [36J], pool boiling in narrow channels and between fins [37J, 38J, 51J], and the pool boiling of mixtures in these same configurations [47J, 65J]. Additional attention was devoted to electro-hydrodynamic effects on pool boiling [62J, 63J, 67J] and of the influence of dielectric coatings [52J, 53J], oxidized surfaces [39J] and plasma sprayed porus coatings [60J] on pool boiling heat transfer rates. The effects of surfactants on nucleate boiling [66J] have also been reported.

Fundamental aspects of heat transfer in thermosyphon reboilers [40J, 55J] and fundamental issues in the modeling of geysers [43J, 49J], as well as the thermal characteristics of thermosyphons applied to heat recovery systems [59J] and the cooling of thyristors [44J], have also been addressed. More modest attention was devoted to pool boiling critical heat flux [56J, 58J] and film boiling [34J, 50J].

12.4. Flow boiling

In convective boiling the enthalpy of the coolant and the state of aggregation of the vapor, as well as the orientation of the channel and the geometry of the heated surface, all influence heat transfer at the heated surface. While [73J] describes efforts to improve the correlation of subcooled flow boiling data, most of the published studies in this category deal with thermal transport rates and limits in specific configurations, including small horizontal tube bundles [89J], various heater orientations [97J], rib-roughened tube annuli [91J], internally, spirally knurled/integral finned tubes [113J], the shell side of integral finned tubes [90J], a vibrating surface [106J] and in micro-fin tubes [75J]. Dynamic instabilities in the flow boiling of refrigerants in heated horizontal tubes [80J], as well as in enhanced tubes [94J, 115J], also received attention, along with studies of the flow and evaporation of liquid films in vertical channels [116J], the void fraction in subcooled flow boiling channels [92J] and the relationship between heat transfer rates and the prevailing two-phase flow regimes [103J].

Much of the archival 1995 literature in this category deals with the enhancement of ebullient thermal transport, thru the use of electro-hydrodynamic forces [70J, 107J], spiral fins and twisted tapes [74J], microgrooves machined into plates [105J], the addition of solid particles [102J], and jet impingement in narrow gaps [78J], on macro/micro-structured surfaces [99J], on pin fin arrays [79J] and with gas injection [117J]. The effect of fouling on enhanced surfaces is also discussed in [72J]. Several publications deal with industrial applications of flow boiling heat transfer, including for the cooling of infrared sensors [71J] and electronic components [98J, 101J] and in the design of capillary-tube expansion devices [82J].

Modeling of the 'boiling crisis' in flow boiling continues to receive significant attention, with ongoing attempts to develop a universal critical heat flux (CHF) correlation for uniformly heated round tubes [110J], to extend the Haramura–Katto model to vertical channels [108J], to deal with the limitations of fluid-fluid scaling [109J], and to develop a theoretical model for flow boiling CHF from short heaters of various orientations [86J, 88J]. Extensive experimental data on dryout in helically-coiled tubes [96J], CHF in twisted-tape-inserted tubes [100J], the effect of channel blockage on CHF for horizontal cylinders [81J], the effects of heater length and orientation on near-saturated CHF [87] have also become available. The interested reader will also find descriptions of the 'boiling crisis' for porous media [111J] and for highly viscous fluids [95J].

Post-CHF and post-dryout phenomena in flow boiling systems are explored in publications dealing with film boiling on horizontal cylinders [76J, 77J], transient film boiling following a vapor explosion [93J], dispersed flow heat transfer in the presence of air [104J], droplet behavior in a dispersed flow in circular bends [112J], and film boiling under reduced gravity conditions [69J]. Thermofluid aspects of quenching, associated with a water wall jet, were described in detail in [83J–85J]. Boiling heat transfer resulting from the injection of subcooled liquid into a tube operating under microgravity conditions is discussed in [114J].

13. Change of phase—condensation

Papers on condensation heat transfer during 1995 were separated into those which dealt with surface geometry and materials effects, those on the effects of global geometry and thermal boundary conditions, papers presenting techniques for modeling and analysis, papers on free surface condensation, and papers dealing with binary mixtures and condensation in the presence of noncondensables.

13.1. Surface geometry and material effects

Geometries considered were commercial integrated fin tubes [1JJ], horizontal 2-D fin tubes [3JJ], wavy-fin tubes [6JJ] and enhanced commercial tubes [2JJ]. Surface material effects were investigated for windows [5JJ], fibrous insulation slabs [7JJ], absorbing fibrous media [4JJ] and paper drying processes [10JJ]. Film-related geometries include a vertical wall [9JJ] and a turbulent falling film [8JJ].

13.2. Global geometry and boundary condition effects

Papers that seem to be more oriented to a particular system geometry include one on condensation within a horizontal rectangular duct [15JJ], in the annulus of a double-tube coil [16JJ] and on a flat plate [17JJ]. Condensation within a gas-loaded thermosyphon [18JJ] system and within solar still systems [11JJ, 12JJ] was also described. Mechanisms for transport as affected by an electric field were discussed [13JJ] and the effect of non-isothermal boundary conditions in an upward flow was analyzed [14JJ].

13.3. Modeling and analysis techniques

Analytical models were developed for condensation inside smooth horizontal tubes [20JJ] and for buoyancy-affected laminar films [19JJ]. Analysis was given for the growth of a tantalum pentoxide film in an atomic layer deposition reactor [22JJ] and heuristic rules were developed for the effects of heat leak location on a cryogenic liquefier [21JJ].

13.4. Free surface condensation

Papers on free surface condensation included one on monodispersed water in pure vapor [26JJ], dropwise condensation in a flowing inert gas [27JJ], direct contact condensation in a subcooled liquid film [25JJ], steam bubbles in subcooled water [28JJ] and the separation zone of the vapor boundary layer [24JJ]. An analysis was presented for flashing flow and heat transfer during an outsurge transient from a small pressurizer [23JJ].

13.5. Binary mixtures and flows with noncondensables

Binary mixtures included CFC114–CFC113 [34JJ], mixtures of R22 and a more volatile component [37JJ] and other non-azeotropic binary mixtures [38JJ]. Condensation was also documented in a HFC124a/Oil mixture [36JJ] and in inorganic compounds where the method of self propagating high-temperature synthesis is applied [33JJ]. Flows with noncondensables were on horizontal surfaces [35JJ], vertical tubes [29JJ], co-current two-phase channel flows [30JJ] and free-falling films [31JJ, 32JJ].

14. Change of phase—freezing and melting

14.1. Melting and freezing of spheres, cylinders and slabs

Planar solidification was carried out in PCMs [1JM], to determine the heat transfer coefficient during freezing in a slab [2JM] and to determine penetration rate of the s/l interface in a slab [5JM]. A numerical study of solidification of a laminar flow within a cylindrical pipe was conducted by [4JM].

Freezing on a variety of cooled surface geometries were also studied. Ice formation on a vertical cooled plate was examined experimentally in a binary aqueous solution by [3JM]. Ice formation on a convex wall and in a return bend with a rectangular cross section were studied experimentally by [7JM] and [8JM], and numerically in a cooled vertical duct by [9JM]. A general finite element model for binary solutions was also presented by [6JM].

14.2. Stefan problems

One numerical study investigated kinetic undercooling in Stefan problems [10JM]. Other experimental and theoretical studies were used in the prediction of metal solidification and eutectic microstructure in Stefan problems [11JM] as well as in complex configurations with two different metals [12JM]. Lastly, an exact solution to the inverse Stefan problem in biological tissue was presented [13JM].

14.3. Ice formation in porous materials

An experimental study was performed to track the silt–sand interface during freezing in a buried chilled pipe geometry [20JM]. A numerical study showed Reynolds number dependence during solidification of a laminar flow in a buried pipe [14JM]. [15JM] performed a numerical study of ice formation on aerodynamic components using a 3-D icing code, while [22JM] also used a numerical code to predict ice accretion in wings. Wet snow accretion was numerically studied by [19JM]. Tracking of temperature and interfaces in multiple domain freezing (particularly biological tissue) was approached by MRI assisted interface tracking coupled with numerical predictions of the temperature profiles within different domains [16JM]. Frosting in fibreglass insulation was studied experimentally [17JM] and numerically [18JM]. Lastly, an experimental study was performed which showed that water properties and structure can undergo novel changes during phase change [21JM].

14.4. Contact melting

A numerical BEM approach was used to assess contact melting on non-isothermal surfaces of arbitrary shape and the ensuing melt flow [23JM]. Direct contact melting in a packed bed was also studied experimentally [24JM]. Experiments and calculations of contact melting following ice making were also studied for optimal ice removal [25JM].

14.5. Melting and melt flows

Metal melt studies included an empirical study of the melt zone of spun Zn ribbon [26JM], a numerical finite volume study of gallium melt in a rectangular cavity [27JM], a model of melt and solidification in thin wires [34JM], numerical models of scrap metal melting [48JM], CO_2 laser melting [35JM], $NbAl_3$ alloy [52JM] and melting in a solid armature railgun [42JM].

Melts within polymeric material were investigated both experimentally and numerically. The melting front in polystyrene (polymer) resin was studied numerically and experimentally in a co-injection process [28JM]. The melt front was studied by control volume (FEM) methods and compared to experiment [29JM]. Melting was studied in a cylinder of polymeric material and the cyclic torsional shear stress evaluated [38JM]. Lastly, laser melting was studied in polysilicon layers by both experimental and numerical techniques [49JM].

A variety of other melt studies were performed, including numerical studies by BEM front tracking [31JM], FEM of the float zone in silicon sheets [50JM], theoretical calculations of the float zone and meniscus shapes [47JM]. In addition, crystallization within a urea melt was studied [32JM]. Location (depth) dependent melt initiation within the interior vs the surface of a material was investigated by use of non-uniform phase transition temperatures [33JM]. Lastly, a computational model of ice cover melting in northern regions of the world was studied [46JM].

Experimental studies of melt flow were conducted in ribbon manufacture of polymers [30JM], melt flow in pipes with nitrate salts [40JM], viscoplastic liquids in tubes [41JM] and high temperature electrostatic levitation during materials processing [44JM]. Other studies included numerical/theoretical modeling of liquid metal flows with gas atomization [36JM, 37JM], flow in germanium float zone of a rotating microgravity melt [39JM], inviscid stagnation of melt flow [43JM], melt spinning [45JM] and pulsed CO_2 laser heating of a melt [51JM].

14.6. Powders, films, emulsions and particles in a melt

Experimental and numerical studies on powders, films, emulsions and particles in a melt were performed. Experimental studies included a powder in tube—silver sheath—study of Bi-2212 tapes with pinhole defects [53JM] and powder melting of Ni–Cr–Al–Y in hybrid clad layers [54JM]. Lastly a numerical model for forced convection in circular tubes during melting of microencapsulated PCM suspensions was studied [55JM].

14.7. Crucible melts

An analytical study of a crucible melt and crystal growth from the melt was performed which showed a dependence on the roughness of the crucible [56JM].

14.8. Glass melting and formation

Glass melting and formation was studied. Numerical studies included: (CFD) of glass melting in flat flame oxy fuel burners to compare firing methods [57JM]; a numerical model of the combustion space coupled to the melt in a glass furnace [59JM]; modeling of glass processing using Glass Pro software [60JM] and a mathematical model of float glass tank surface using a SIMPLEC scheme [61JM]. An exact solution of laser heating and melting of glass–metal two layer systems [58JM] was also performed.

14.9. Welding

Numerical studies of welding included modeling of arc welding with buoyancy, surface tension and EM forces in the weld pool [62JM]; heat and metal transfer in arc welding using argon and helium [63JM]; adaptive pulsive technology [64JM]; pulse-welded solidification and microstructural changes [65JM]; 3-D numerical model tungsten welding in inert gas [66JM]. Lastly, a mathematical model of solidification microstructure was performed [67JM].

14.10. Enclosures

Numerical studies on phase change in enclosures included natural convection dominated melting of a PCM [69JM] and transient solidification [71JM]. Experimental studies included crystallization of a binary melt on a vertical boundary of an enclosure [70JM] and contact melting in a rectangular capsule for thermal energy storage [68JM].

14.11. Nuclear reactors

Numerical modeling of transient heat transfer in radially and axially diluted nuclear fuel rods with high specific heat and high resistance to oxidation and ignition were studied to assess the impact on delayed melt during nuclear accidents [72JM, 73JM]. Core melt accidents were studied with the TPCONT computer code to assess the effects of thermal hydraulic loads in pressurized water [74JM]. Lastly, an experimental study of thermite melts in nuclear technology was performed [75JM].

14.12. Energy storage

Sensible heat storage was studied by closed form analytical methods to compute thermoeconomics of a large liquid thermal energy storage bath [76JM]. Other studies included thermal energy storage by melting and solar energy in a power plant [77JM]; latent heat energy storage in $MgCl_2 \cdot 6H_2O$ using natural convection in finned vs unfinned storage units [78JM]; and energy storage in organic material which increases the energy storage in wallboard up to $12\times$ [79JM]. In addition, an experimental and theoretical evaluation study of latent heat storage ($CaCl_2 \cdot 6H_2O$) in a solar water heating system [80JM]; a second law optimization of PCM melting was performed by [61JM]; and a semi-analytical model of melting using turbulent forced convection of PCM in a tube were also presented [82JM].

14.13. Solidification during casting

Solidification during casting was studied by a micro and macrostructure model of Al alloy during casting [83JM]. A numerical model of Al alloy solidification was also performed during squeeze casting [84JM].

14.14. Mushy zone—dendritic growth

Experimental studies of hypo and hyper eutectic solutions and dendritic growth in the mushy zone of a V shaped sump filled with a PCM was studied [85JM]. Numerical/theoretical models studied the effect of external heat extraction during dendritic growth in Fe–Cr–Ni system [86JM]; the effect of natural convection on dendritic crystal growth in a stagnant film around a sphere [87JM] and growth and interaction of unstable fronts in the mushy zone [88JM].

14.15. Metal solidification

Experimental metal solidification studies investigated: fiber engulfment at a plane solidification front [89JM]; undercooling and heterogeneous nucleation in 63Sn–37Pb solder pastes [94JM]; directional solidification of metal in a crucible compared to theory (analytical) [97JM]; assessment of morphology and segregation after directional solidification in CuMn alloys [99JM] and the effects of shifting thermal properties upon relaxation and crystallization in germanium films [100JM].

Numerical/theoretical studies of metal solidification included studies on finite element modeling with high efficiency numerics [91JM] and a theoretical study using the latent heat method on a binary alloy system [92JM]. Dissolution kinetics were studied in ferroalloys [93JM], and thermal contact resistance between casting and metal were modeled for aluminium [90JM]. Several numerical analysis examples of metal solidification were presented [95JM]. Other investigators studied transport phenomenon in metal alloy solidification [96JM]; the effects of turbulence during EM stirring in the melt on solidification [98JM]: melt spinning of Fe80B20 alloy solidification [101JM] and solidification of a planar metallic coating on a substrate [102JM].

14.16. Crystal growth from melt

Studies concerned with Czochralski crystal growth included: a study of radiation in carbon contamination incorporation [103JM]; an experimental study of control of oxidation induced stacking faults (OSF) [106JM]; a review of crystal growth modeling and experiments as well as flow visualization of flow instability [107JM]; the effect of growth atmosphere on convection in melt of Li–Ta–O_3 [113JM]; an experimental study of oscillatory natural convection effects on crystallization [117JM]. Czochralski crystallization studied by numerical/theoretical techniques included: an analytical study of GaAs process in liquid encapsulated crystals [111JM]; a theoretical study of dislocation reduction in gallium arsenide [116JM]; a study of dislocation generated in semiconductor crystals [118JM]; the effect of internal radiation on the crystal during melt [119JM]; high resolution massively parallel computation of 3-D melt flow during Czochralski oxide growth [120JM].

Crystallization by the Bridgman technique was also studied. Investigations included a theoretical (quasi-steady) model of vertical Bridgman growth of cadmium zinc telluride crystals [108JM]; a theoretical model of vertical Bridgman growth of cadmium zinc telluride of Zn segregation [109JM]; and an experimental and numerical study of Marangoni convection around voids during Bridgman crystal growth [112JM].

Crystal growth was also studied by numerical/theoretical techniques. Studies were performed in a 1-D transport model of liquid phase electroepitaxy [104JM]; a numerical galerkin FEM model incorporating buoyancy and thermocapillary effects [105JM], a theoretical study (pseudo steady state) using traveling solvent method [110JM], kinetics of macrostress in stagnant medium of KDP crystals [114JM], a model of the silicon floating zone process [115JM] and a study of growth under low and hi pressure [121JM].

14.17. Casting

Casting modeling studies including thermocapillary and buoyancy effects numerically investigated in steel slab caster molds [123JM]. Other numerical studies included simulations to identify possible locations of shrinkage and defects to improve manufacture of specific casting shapes [122JM], an analysis of temperature gradients across blow molded/casting shapes [122JM], an analysis of temperature gradients across blow molded/casted parts compared to experiment [124JM] and prediction of the casting of metal and the ensuing thermomechanical stress in a spherical geometry [126JM]. Lastly, casting and melting improvements at Roehrenwerke Bous plant was reviewed [125JM].

14.18. Splat cooling

Remelting during splat cooling of two liquid metal droplets impacting sequentially was studied by theory and experiment [127JM].

15. Radiative heat transfer

The papers below are divided into subcategories which focus on the different impacts of heat transfer by radiation. Papers describing the development or application of models dominate the literature on radiative heat transfer. Papers focusing on the numerical methods themselves are reviewed in the numerical methods section under subcategory radiation.

15.1. Influence of geometry

The calculation of view factors for different geometries continues to be of interest. Several common geometries are discussed in [1K, 7K, 8K]. Multidimensional geometries are studied in [2K, 5K]. Radiation problems of first wall facilities in fusion devices were demonstrated in [3K]. The influence of the surface geometry on emissivity and reflectivity is pointed out in [9K]. The radiation in micromechanical structures is modeled in [4K]. The influence of polarization effects in the radiative heat transfer in arrays is also studied [6K]. Papers discussing enclosures and processing chambers are referenced in the section on radiation combined with convection and conduction.

15.2. *Participating media*

Papers in this category can be divided into those which focus on emission and absorption of the media and those which deal with scattering. Radiation transfer in molecular gases such as air, CO_2 and H_2O is discussed in [14K, 18K, 36K, 38K, 45K]. A spectral line based model for nonisothermal, nonhomogeneous gray gases is developed in [13K]. [34K] studies the absorption of metallic particles; absorption due to intersubband transitions in doped semiconductors is investigated in [20K]. Several papers focus on the influence of anisotropic scattering of radiation [25K, 28K, 29K, 33K]. Radiative transfer in gray, isotropically scattering media is modeled in [32K]. Low temperature systems in which scattering is important include fibrous media [24K, 26K]. Investigations of radiative transfer in high temperature systems focusing on absorption, emission, and scattering include studies of porous radiant burners [42K, 43K], and combustion systems [12K, 16K, 19K, 39K], high temperature two phase flow [27K], and fluidized beds [17K, 46K]. A related topic is the radiative interaction of multiple liquid pool fires [44K]. The effects of heating of a semi-transparent medium on ignition characteristics were reported in [15K]. The in-depth absorption of incident thermal radiation was studied in [31K]. Theoretical models were proposed for radiative transfer in cylindrical participating media [47K] and for media in rectangular enclosures [37K].

Several papers deal with the interaction of radiation with particles. The effects of irradiation of micrometer sized particles was studied in [11K, 21K]. Disperse suspensions of compound particles were proposed as material for radiation trapping surfaces [22K]. Investigations on particles with directionally dependent absorption is studied in [30K].

Refractive index effects have to be accounted for in the cooling of semitransparent radiating layers [40K, 41K]. The effects of wall emissivities on radiation heat transfer in glass tank forehearths were pointed out in [35K]. Wavelength dependent emissivities were used to model radiative heat transfer in semiconductor wafers [10K]. Another study was concerned with the modeling of radiative heat transfer in metalorganic chemical vapor deposition reactors [23K].

15.3. *Radiation combined with convection, conduction, or mass transfer*

The interaction between radiative, conductive, and convective heat transfer was studied in numerous basic studies [49K, 55K, 61K] as well as applied investigations of furnaces [56K, 70K, 74K], boilers [50K], and packed [64K] and fluidized beds [54K, 58K, 65K]. The combined radiative–convective–conductive heat transfer in a soaking pit was modeled three-dimensionally in [63K]. The impact of radiation in turbulent, nonequilibrium and chemically reactive flow was studied in [52K, 53K, 59K, 68K]. Radiation from shock layers was modeled in [57K]. Combined laminar convection and radiation was investigated in [60K, 71K, 75K]. Combined convection and radiation also plays an important role in atmospheric heat transfer [51K]. The effect of radiative and convective heat transfer in power cables was demonstrated in [48K]. Combined conduction and radiation was demonstrated to play a limiting role in optical recording [66K].

Combined conductive and radiative heat transfer was analyzed for vacuum insulating panels [67K] and for active radiator tiles acting as thermal valves [72K]. Combined heat transfer is also important for high-Tc superconductors [69K]. Transient conductive and radiative heat transfer in silica windows was analyzed in [73K]. Pilot scale investigations of the infrared drying of paper were reported in [62K].

15.4. *Intensely irradiated materials*

A number of papers were concerned with the applications of intense microwave or laser radiation. High intensity laser radiation was used to study the heating of highly absorbing particles [79K]. Nonlinear effects due to the high intensity can become important in laser-liquid interactions [80K]. Analytical solutions for the three-dimensional heat conduction in coating-substrate assemblies radiated by moving or stationary laser beams were presented in [77K].

The heating of dielectric systems by microwave radiation was investigated in [76K]. Application of microwave radiation for the continuous flow heating of orange juice were reported in [82K], the thawing of frozen soils and gravels with microwaves was demonstrated in [78K]. The importance of the mode distribution of microwave fields for a fluidized bed was pointed out in [81K].

15.5. *Experimental methods and properties*

Single- and dual-wavelength thermometry was used to measure the emissivities of refractory metals and carbides subject to thermal and hydrogen effects [86K]. Multiwavelength methods were employed to measure wall temperatures of quartz radiant heating tubes [83K]. The effects of oxidation on localized heat generation and dielectric breakdown in low-density polyethylene films were studied using thermography [88K]. Electrodeposited polyaniline films were analyzed by photothermal spectroscopy [87K]. The performance of a hemispherical radiation flux meter was evaluated in [85K]. This device is proposed to differentiate between radiative and convective heat transfer in combustion chambers. A new procedure for calibrating radiative and convective flux profiles measured in a laterial ignition and flame spread test apparatus were introduced in [84K].

16. Numerical methods

A considerable amount of research has been focused on the development and application of numerical methods. Partial differential equations governing heat transfer and fluid flow are solved by new procedures and algorithms. Numerical methods are also applied to a variety of practical problems. In this review, the papers that mainly describe the application of numerical methods to specific physical problems are included in the appropriate application category. This section focuses on papers that deal with the details of numerical methods.

16.1. *Numerical solution schemes*

Several extensions of well-established iterative algorithms for the solution of the discretized equations are described in [10N]. An efficient and robust solver based on the block-correction procedure is proposed for elliptic differential equations [5N–

7N]. An operator splitting scheme has been described for three-dimensional temperature distribution [8N]. Reference [4N] describes a multifrontal algorithm for the solution of large systems of equations. The boundary element method (BEM) is presented for three-dimensional heat conduction [2N]. The BEM is also used for shape sensitivity analysis [1N]. An orthogonal collocation technique is employed for solving boundary value problems [13N]. A posteriori error estimation procedure is described in ref. [9N]. An unstructured method is described for the transport processes in porous media [11N, 12N]. An additive correction multigrid method is developed for unstructured grids [3N].

16.2. Treatment of convection and diffusion

The convection–diffusion problem is handled by the boundary element method [15N]. Reference [22N] presents a locally modified upwind scheme. An integral transform technique is used for convection–diffusion problems [14N]. A higher-order scheme is proposed for strong convection [23N]. For convection–diffusion problems, matrix preconditioning [18N] and preconditioned CG methods [19N] are used. Several articles provide a comparative evaluation of methods for convection–diffusion equations. A higher-order bounded scheme is evaluated in [16N], while the evaluation of several schemes is reported in [24N]. Reference [20N] provides an assessment of schemes based on flux-corrected transport. Several iterative schemes for convection and diffusion are compared in [17N]. A posterriori error estimate for convection–diffusion problems is provided in [21N].

16.3. Solution of flow equations

Convective heat transfer is inseparably coupled with fluid flow. Extensive work is being done on methods for solving the equations governing fluid flow. An accurate discretization for the Navier–Stokes equations is described in [27N]. An improved discretization is given in [29N]. A staggered method for triangular grids is presented in [30N]. Reference [32N] provides an equal order version of a method for triangular elements. A parallel finite-element algorithm is given in [26N]. A finite-element formulation based on p-version least squares is presented in [25N, 28N]. Multigrid techniques for the flow equations are employed in [31N, 33N].

16.4. Phase change

Finite element methods are compared for solving the Stefan problem [36N]. A numerical technique is described for the analysis of phase change with the mushy zone [35N]. For the prediction of free dendritic growth, a three-dimensional cellular automaton model is used [34N].

16.5. Radiation

Reference [40N] presents a comparison of reciprocity and closure enforcement methods for the calculation of view factors for radiation. Different solution methods are examined [37N] for discrete ordinates formulation. The discrete maximum principle is used for including radiation in finite-element analysis [39N]. Uncertainty analysis is presented [41N] for diffuse-gray radiation in enclosures. A numerical study is made [42N] of the instability induced by radiation. for the inclusion of surface radiation in a combined flow, heat, and mass transfer computation, a multigrid solver is used [38N].

16.6. Other studies

Conjugate heat transfer in a washer-dryer system is numerically analyzed [44N]. The Reynolds stress models are used in modeling dump combustor flows [45N]. Different two-equation turbulence models are compared for the computation of indoor air flow [43N].

17. Transport properties

Activity in this area was strongly motivated by interest in specific systems rather than a concern for general formulation.

17.1. Thermal conductivity and thermal diffusivity

Here, a group of studies are concerned with: thermal conductivity of an active carbon bed (in vacuum, He, Ne and Ar atmospheres): sea-bed rock; two-layer systems; polycrystalline $Cu_{2-x}S$ and air/water cooling of spherical and cylindrical shapes representing food products [1P–7P].

17.2. Viscosity

The role of viscosity in modeling coal-ash particles sticking and heat transfer in packed beds is examined [8P, 9P].

17.3. Thermodynamic data

As with transport properties work appears to focus on fluid groups or specific applications. Noteworthy among these is the comprehensive compilation of existing fluorinated hydrocarbon thermochemistry, the validation of the coupled vibration–chemistry–vibration model of chemical reactions, and the importance of low temperature helium properties in the design of superconductors [10P–17P].

17.4. Thermodynamic cycle analysis

Significant effort is invested in the modeling of various thermodynamic cycles. For Carnot cycles (forward and reversed) the connection between optimal performance for irreversible heat flow is examined as is the performance of a combined Carnot cycle (two single Carnot cycles in cascade), and the maximum specific output of a two-stage endoreversible combined cycle [18P–20P].

17.5. Forward cycles

Among the papers in this area the Rankine cycle is analyzed using low temperature heat sources, a simulation procedure predicts the combined cycle performance using main component behavior, and a Brayton cycle with internal heat source examined for optimal second-law efficiency [21P–26P]. For reversed cycles a number of papers attempt to model the performance of irreversible refrigerators and make explicit the relation of optimal performance of such systems to optimal heat exchanger area [27P–29P]. Rekindled interest in the absorption cycle, because of energy and environmental concerns, has led to modifications of the conventional cycle configuration and the modeling of irreversible systems by finite rate heat transfer [30P–32P]. Irreversible heat pumps, transformers, chillers and gas liquefaction plants are accorded like treatment [33P–38P].

18. Heat transfer applications—heat exchangers and heat pipes

Activity continues on the various aspects of heat exchangers: analysis, control, performance and materials.

18.1. Heat exchangers—design

Several models are used to analyze heat exchanger operation: an axial dispersion model applied to plate exchangers, one which evaluates radiative heat fluxes in tube exchangers, the linearization of a discrete-time, non-linear exchanger and the weighted residuals method applied to mixed convective heat transfer for tube bundles between plates. Control systems are also considered [15Q, 29Q, 33Q, 35Q, 37Q, 39Q].

Design considerations range from an assessment of research on heat and mass transfer in modern heat exchangers to the exergy optimization in a specific application. Other works feature a new design method for baffled exchangers, correlation for optimum baffle spacing, transients and evaluation of design flexibility [2Q, 12Q, 14Q, 16Q, 19Q, 28Q, 30Q–32Q].

Compact heat exchangers are studied in several contexts: use in an air turboram- jet, in conjunction with vortex generators, and heat transfer and pressure drop correlation for strip-fin designs [5Q, 17Q, 20Q, 24Q, 34Q].

In the condenser area the heat transfer and mass flow in power station steam condensers are modeled, the feasibility of heat recovery from the condenser of a vapor compression refrigeration system is investigated and the thermal and fluid-dynamic behavior of double-pipe condensers and evaporators studied numerically. A Nusselt analysis of a vertical axis rotating condenser is presented and the performance of dehumidifiers reported [7Q–9Q, 13Q, 21Q, 23Q, 26Q, 27Q].

Heat exchanger networks are examined by automated synthesis, direct synthesis with unequal film coefficients and tested with uncertain flowrates [3Q, 22Q, 42Q, 43Q].

A number of papers consider special circumstances of heat exchanger usage: cryogenic applications, heat-pumps, a plastic shell-and-tube exchanger, brazed plate exchangers, evaporators and a night-sky radiator for cooling water [1Q, 4Q, 6Q, 10Q, 11Q, 18Q, 25Q, 36Q, 38Q, 40Q, 41Q].

18.2. Direct contact exchangers

Efforts focus on cooling towers, specifically those designed and used in systems for human comfort. A spray-type tower is analyzed, a counter-flow tower modified to pre-cool inlet air, and the falling-film type modeled. The ‘apparent enthalpy’ is proposed for use in graphical, analytical and E-NTU design methods. Experimental results are reported on simultaneous heat transfer and gas dissolution for direct contact condensation of steam on water in the presence of CO_2 [44Q–50Q].

18.3. Enhancement

Techniques for promoting heat transfer continue to be explored. The performance of baffled tube exchangers with agitated or oscillatory flow is reported and passible enhancement techniques applied to compact bubble absorber design [64Q, 65Q, 67Q, 68Q].

A number of papers concentrate on geometrical aspects: helicoidal pipe with finite pitch, rotating helical pipes, spirally fluted annuli and tubes, internally grooved horizontal tube, and compact louvered fin surfaces [51Q, 52Q, 57Q–60Q, 63Q, 66Q, 73Q, 74Q].

Plate-fin exchangers are considered in connection with phase change materials. Perforated exchangers with vortex generators as fins and a review of the use of longitudinal vortices comprise the work in this area [53Q, 55Q, 56Q, 62Q, 70Q–72Q].

The influence of Prandtl number, wall conduction and heat transfer reversal are reported [54Q, 61Q, 69Q].

18.4. Fouling/surface effects

Exchanger performances in practice often encounters fouling. A group of papers study fouling during pyrolysis of hydrocarbons, particulate fouling in a plate type, the influence of ferric chloride on silica fouling, fouling and slagging in coal-fired boilers and minimizing cooling water fouling. Monitoring and mitigation techniques are modeled and aspects of operational practices designed to minimize fouling are presented [75Q–85Q].

18.5. Regenerators/recuperators

Regenerative exchangers are studied experimentally, modeled for the Stirling cryocooler, and designs presented for a methane–steam reformer used as a chemical recuperator for a gas turbine power cycle [86Q–89Q].

18.6. Thermosyphons (heat pipes)

Reported work includes analytical models, experiments and application in a number of areas. Modeling and simulation cover a water-in-steel heat pipe energy recovery system, micro heat pipes, flat plate versions, transient simulation of rotating heat pipes, thin film heat transfer in the evaporator of heat pipes, high-capacity external artery designs and a disk-shaped asymmetric heat pipe [90Q, 93Q, 95Q, 98Q, 102Q, 104Q, 105Q, 107Q].

Experiments range from transient experiments on an inclined copper-water type and energy extraction from grounding a volcanic zone. Other experiments consider an array of pipes for convection cooling, the freezing blowby phenomena, start up characteristics of a pipe from the frozen state and pumped heat pipe for high-flux use [91Q, 94Q, 96Q, 97Q, 101Q].

Heat pipe applications embrace a spectrum ranging from engine piston cooling operation to earth orbiting platforms, space stations and planetary bases. Several studies describe application to the semiconductor and electronic packaging fields [92Q, 99Q, 100Q, 103Q, 106Q, 108Q, 109Q].

19. Heat transfer applications—general

19.1. Aerospace

The mass flow rate and heat transfer during start of a liquid propellant rocket engine was modeled [1S]. An analysis [6S] studied ignition, flame spreading and heat transfer to the propellant. The study of heat transfer in an exhaust diffuser of a modern air breathing engine was chosen [17S] to test the behavior of ceramic composites. The internal flow in a solid fuel rocket was studied numerically for transient operation [13S]. A two phase cooling system is proposed [10S] for the thermal control of a space craft. The pumping work is produced thermodynamically in the heat transport loop. Heat generation in ammonia-treated solid rocket propellant is modeled [19S].

A new analytic solution is presented for the shuttle heat transfer rate [2S]. A Navier–Stokes code with species balance conditions on the charring surface can be applied to the design calculations of the Mars pathfinder trajectory [5S]. Detailed heat transfer rate distributions over the windward surface of an orbiter configuration were measured [18S]. Monte Carlo and Navier–Stokes axisymmetric calculations [9S] are applied to hypersonic low density flow over a 70° blunt cone after body. Experimental results and analysis are combined [7S] to determine the recombination of atomic species in a boundary layer. Optimization of cooling panels of a hypersonic aircraft is explored [21S].

A simplified model is used [4S] for the analysis of reaction dynamics in hypersonic rarefied flow to study the influence of oxygen dissociation on the prediction of aerothermal coefficients. A reaction scheme is established for O and N recombination on the surface of reentry vehicles [8S]. A numerical study of the flowfield around a 70° blunted cone uses the Monte Carlo method [11S]. The effects of geometry and angle of attack on aerodynamic heating of an aero-assisted space transfer system [20S] are studied. The ignition of energetic materials is influenced [3S] by the complex heat exchange between energy source and ignited substance. The transition region between continuum and rarefied regimes is studied [12S]. Thermocapillary convection in microgravity was measured aboard the USML-1 space lab with silicone oil in an open circular container [14S]. Nucleation from solutions in 1:1 microgravity is initiated [15S] by injecting a small amount of concentrated heated solution into the slightly super-saturated cooled host solution. The use of closely packed brush-fibers on opposite walls is proposed for heat exchangers of spacecraft [16S].

19.2. Bioengineering

A model [24S] of the human thermal system for the prediction of thermal comfort differs from previous ones by a more precise description of heat transfer by blood flow and inclusion of arteriovenous anastomoses. Energy conservation in swimming is formulated [22S] in terms of four functions of the swim speed, the consumed power, two forms of mechanical power and the thermal power loss. Simple geometric and heat and mass transfer models are compared with measured data [23S] for the chilling of pigs.

19.3. Digital data processing, electronics

Thermoelectric coolers to remove heat from hot chips are now available [34S]. The future of water cooling for electronic technology is evaluated [33S] as well as that of two-phase component coolers [29S]. The electric thermal network analogy is used to study thermal behavior of electronic components. The present paper presents a new technique [31S] based on asymptotic wave form evaluation. Theoretical predictions on gas–liquid–vapor flow in narrow parallel plate passages are compared [26S] with experimental results for wall temperatures, heat transfer and pressure drop. A computer simulation studies the interface shape, heat transfer and fluid flow of the floating zone growth of large Si crystals [32S]. Process induced defects cause difficulties for the lamination process of printed circuit boards [25S]. Anisatropic high temperature conductors show critical current densities dependent on the direction of an external magnetic field [27S]. Superior noise amplification has made arsenide power amplifiers attractive for electronic applications [28S]. The results of thermal modeling of free convection cooled electronic products are compared with experimental data [30S]. Heat, mass and momentum transfer has been numerically analyzed [36S] for a curing oven used in microelectronic manufacturing. Thermal control of electronic equipment is being reviewed [35S].

19.4. Energy

A measure of turbine cooling performance was developed [57S] as a yardstick in comparing cooling systems.

Heat transfer rates at the surface of moving gas turbine blades were measured through the changes in microstructure of the blade material [58S]. Time averaged heat transfer coefficients on turbine blades depend on the mean turbulence intensity regardless of whether the turbulence intensity is from unsteady wakes or from grids [70S]. Phase resolved pressures were measured on the surface of the Space Shuttle two stage turbine [44S]. Heat transfer on the blade pedestal with fillet was measured [66S] by the method using thermochromic liquid crystals.

A numerical study [40S] presents a finite-element solution to heat transfer in a annular combustion chamber and a model [61S] for description of axisymmetric swirl flow is based on Reynolds equation with an e–k model of turbulence. The trailing edges of turbine blades are often roughened by tapered turbulators. Liquid crystals were used [65S] to examine their influence on the effectiveness of the passages. Heat transfer to the combustor walls in power stations is dominated by radiation due to their size [46S] whereas in gas turbine combustors it provides only part of the heat transferred [48S].

Previous models predicted that heat transfer in low flow regions of the cylinder head of diesel engines is small. Experimental results find that they are as high as in high flow regions. This is now also confirmed by a new model [39S]. One paper analyzes heat transfer in the regenerator of stirling engines [59S].

The performance of the Halden boiling heavy water reactor is investigated under adverse core cooling conditions [62S]. A computer code models water chemistry, corrosion and crack growth rate in boiling water reactors [68S]. A second law analysis is applied to the LaSalle County Nuclear Station [43S]. Heat transfer models are also used to describe fragmentation [47S]. Magnetohydrodynamic flow characteristics and heat transfer obtained from experiments are summarized [63S] for fusion reactors. A study is concerned with heat exchanger and heat transport systems in the Hylife II fusion power plant [52S]. An analysis looks into the performance of heat transport systems [53S].

Flue gas flow through a recovery boiler was numerically simulated [60S]. Results agreed with measurements. Temperature field and electric field distribution at the joint of a dc power cable were analyzed [64S]. Heat transfer and pressure drop in the various zones of a feedwater heater were studied using the Delaware method [67S]. Steam explosion experiments [51S] demonstrated the difference between the effect of stored energy and of propagation in the premixed zone. Thermodynamic analysis of the heat recovery systems of a combined power plant [56S] reduces irreversibilities. Heat transfer is analyzed [71S] for an inclined two-phase thermosyphon. High temperature heat transfer fluids are discussed [42S].

The improvement of the heat transfer rate of heat pumps using sodium carbonate is crucial for an efficient system [55S]. The effect of irreversibilities (heat transfer and electric resistance) can be lumped in a single parameter [49S]. The mechanism by which heat is transported from the cold to the warm end of the generator is discussed for a pulse-tube refrigerator [41S]. The energy loss is discussed for a shower cooler [69S]. Experiments research the hydrodynamic and heat transfer processes [50S] in cooling towers with fluidized beds. The installation of a cooling system in the Channel Tunnel was made necessary [45S] because of the length of the tunnel and its depth below the sea bed. The experimental equipment used in the study of a heat transformer using a water–lithium chloride system is described [37S].

19.5. Environment

Systematic studies on thermal environmental comfort were done with a group of 30 persons [84S]. Thermal discomfort can be avoided by optimizing air velocity and temperature [77S].

Radiation barrier insulation and highly reflecting ceramic paint are compared with respect to their effectiveness [83S]. Phase change insulation can protect [82S] against cold in winter and heat in summer. Envelope designs of 83 completed commercial buildings in Hong Kong were surveyed for their every efficiency [81S]. Heat transfer by natural convection along cold window surfaces was measured [88S] in a climate chamber. The effect of angle and absorptance on heating and cooling loads was studied [74S] on buildings in Seoul. A paper focuses [80S] on thermal insulations of roofs. In desert regions, daily energy storage in building envelopes affects the thermal load strongly [72S]. Flow and heat transfer of the air in green houses influences heat and mass exchange between plants and air strongly [91S]. The impact of air leakage on heat transfer through insulated walls was measured [73S] and analyzed. Computer models can now predict [85S] with good accuracy the heat losses of clothed persons. The potential of high performance insulation for refrigerators using non-CFC refrigerants [78S] is discussed. Environmental effects have to be considered [79S] in electric arc operations.

Fire experiments were conducted [76S] on 20 full scale compartments. A model simulates the interaction of a two-layer fire with a sprinkler [75S]. A series of tests in Japan investigates [90S] the behavior of concrete structures at high temperature. The real time modeling of forest fires in Mediterranean ecosystems can be planned [89S].

A geothermal program of the U.S. Geological Survey has been revitalized [87S]. Yunnan Province in Southwest China has promising geothermal resources [86S] which are evaluated.

19.6. Manufacturing

A large number of papers on manufacturing processes were concerned with casting. Most of them modeled the process for computer analysis. One of the experimental papers investigated the interface heat transfer in free-jet casting [92S]. Cooling and solidification were simulated in two papers [93S, 95S] for continuous casting as was the influence of air gaps in aluminium rotary castors [97S] and strip castors [101S]. A one-dimensional model is used to study solidification shrinkage and macro-segregation near the surface [99S]. An analysis [106S] is based on a three-phase model of the mushy zone. The solidification structure in a twin roll casting process is clarified by experiments and analysis [109S, 111S]. Heat transport and solidification are modeled and also studied experimentally in two papers [113S, 114S] for electromagnetic casting. The involved turbulent flow, heat and solute transport in various casting processes and the stress generation is studied in several papers [100S, 115S, 117S, 118S].

Temperature distributions in machining are calculated using the steady two-dimensional energy equation with the coolant temperature as boundary condition [107S, 108S]. Mud cooling has advantages [110S] for drilling processes.

The energy partition to the workpiece for grinding was modeled [98S, 121S] and determined experimentally for ceramics [105S] and steels [103S].

A flash smelting process is studied [104S] by computer simulation and experiments. A heat transfer model is developed as aid to the design of a reheating furnace [120S] and is used to predict skidmark formation. Heat transfer and recrystallization of steel during hot rolling are modeled [94S, 119S]. Heat transfer in injection molding systems with insulation layers and heating elements is studied analytically and by experiments [102S]. Measurements agree reasonably well with predictions. Transient heat transfer and consequent evolution of microstructure were measured in the early stages of solidification of an alloy on a water cooled chill [112S] instrumented with thermocouples. Maxwell's electromagnetic equations coupled with Fourier's heat transfer equation are solved [96S] numerically to simulate microwave heating of a dielectric material. Reflow soldering with nitrogen injection is simulated by a model that is capable of predicting thermal and species concentration phenomena [116S].

19.7. Processing

A theoretical model is proposed for the curing of thermosetting polymers [137S] and an enthalpy solution method is developed to describe cooling and solidification of polymers in a blow molding process [131S]. Heat transfer and particle deposition is studied experimentally [130S] and analytically [128S] for particle deposition. The limits of applicability are investigated [125S] for the analysis of augmentation in heat transfer using dilute gas–solid suspensions by comparing computer solutions with experimental results. The relationship between heat transfer and metallurgical transformation are explored [124S] for spray quenching. The equations describing heat and mass transfer during industrial drying are solved using Galerkin's method [126S]. An attempt is made [140S] to apply a mathematical model to the heat and mass transfer process in spray drying with strong swirl flow. Flow and heat transfer in a single-screw extruder for polymers is studied numerically [138S] and the results are compared with experimental ones of Newtonian and non-Newtonian fluids. The equation for energy transfer and crystallization kinetics are used [123S] to study processing conditions for thermoplastic polymers. A thermal analysis [129S] studies the curing of thermoset, hoop-wound structures using infrared heating. A mathematical model is developed [122S] to predict the time-temperature history of devolatilization of large coal particles in a convective environment. The accuracy of three approximate solutions is examined for the radiative heat transfer in a flash smelting furnace [139S]. Transient studies are required [127S] to determine glass furnace efficiency and operational flexibility. The interacting heat and mass transfer and combustion determine the efficiency of a brick making kiln [136S]. Mathematical models predict the temperature histories of meatballs in forced and natural convection baking and boiling [132S]. Unsteady heat and mass transfer is studied numerically [133S, 134S] during absorption and desorption in a metal–hydrogen reactor. Momentum, heat, and mass transfer are modeled incorporating structural nonuniformities in fixed-bed reactors [135S].

20. Solar energy

Reviewed papers include research on solar thermal technologies, resource assessment and use of renewable energy and energy conservation in buildings. Papers that do not address heat transfer issues, for example, papers dealing specifically with photovoltaics or wind energy, are not included.

20.1. Radiation characteristics and related effects

The majority of the papers address algorithms or numerical models for generating synthetic radiation data or for interpreting/extrapolating limited meteorological data. Reference [7T] discusses the influence of measurement interval on clearness index. Stochastic modeling of diffuse radiation is suggested as a technique to capture transient behavior of solar thermal systems [12T]. Reference [3T] presents a method of interpreting satellite irradiance maps and then decomposing them into spatial averages and gradients. Determination of the Angstrom turbidity from the ratio of direct to global radiation on an horizontal surface is presented for Valencia [11T]. The use of a topographical map and radiation data from a free horizon site can provide horizon screening effects for complex high latitude topography according to [10T]. Equations that can be used to computerize the American Institute of Architects' graphical method of plotting sun-paths and shading are given by [8T]. Reference [6T] shows that accurate simulation of photovoltaic systems requires minute-by-minute radiation data. Papers [1T, 2T, 4T, 5T, 9T] concern development of measurement techniques.

20.2. Non-concentrating collectors

The maturity of the field of non-concentrating (primarily flat-plate) solar collectors is reflected in the limited number of papers. Experimental study of an evacuated flat-plate collector shows that the use of argon rather than air in the evacuated space can decrease conduction losses by as much as 50% at 10 Pa. Numerical analysis indicates krypton and xenon may further reduce losses [14T]. A relatively new concept is an hybrid photovoltaic/thermal collector in which the solar cells are the absorber. Reference [15T] predicts temperature-dependent electrical and thermal output of the hybrid collector. The effects of collector aspect ratio [23T] and fin design [21T] are studied for conventional flat-plate collectors. Experimental study of buoyancy induced air flow collection [16T] and packed-bed air collectors [13T] are presented. References [19T, 20T, 22T] present analytical models and experiments of flat plate air collectors. Staggered fin rows under the absorber plate are used to increase heat transfer between absorber and air [17T]. An indoor test facility that simulates a collector and thus allows testing of other components is discussed by [18T].

20.3. Concentrating collectors and systems

Papers cover use and design of parabolic-trough collectors, measurement and models of heat transfer processes in receivers, power plant operation and description of test facilities.

A survey of the patents for low and intermediate parabolic concentrating collectors indicates little activity since 1980 [32T]. Recent activity focuses on high temperature applications. New concepts include use of fins in a parabolic trough [31T] and baffles in the cavity of a compound parabolic concentrator [27T]. Control of temperature in a distributed field by modification of mass flow is modeled in [46T]. Other models identify optimum acceptance angles [45T] and heat transfer analysis of compound parabolic concentrators [29T]. A ray trace of an off-axis system is used to characterize a facility at the University of Florida [43T].

Determination and reduction of radiative [41T] and convective heat losses [35T] in receivers is discussed. Heat transfer analysis of a volumetric receiver with tapered ducts provides an analytical expression for view factors [30T]. Reference [28T] presents measurements of flux density on a flat receiver/heliostat system. Experiments and analysis of molten-nitrate salt cold filling receiver panels and piping examine the feasibility of cold filling to reduce parasitic losses [39T]. The cause of thermal fatigue of receivers at the White Cliff power plant is discussed and methods of avoiding the problem are suggested [24T].

Several papers address development and analysis of solar thermal power production. References [38T] and [37T] model heat engines and [44T] considers stirling engines. The feasibility of power generation with large vertical collectors through which air rises and powers a turbine is examined by [40T]. These collectors must be 500 m tall to achieve 1.6% efficiency of conversion from solar radiation to mechanical power. A pilot project to determine the performance of a magnesium hydride/magnesium storage for steam generation is discussed for use with high grade industrial waste heat or solar concentrators [26T]. A thermodynamic analysis of a combined gas turbine with solar heating and liquid natural gas refrigeration is contained in [25T].

Flux maps of the 400 m_2 dish concentrator at the Australian National University are presented in [33T, 34T]. Reference [36T] discusses two-stage concentrators which allow concentration of up to 90% of the maximal. The effects of concentrated solar energy on steel are modeled in [42T].

20.4. Buildings

Energy conservation in buildings continues to attract significant research on materials and simulation models. Papers that relate primarily to windows include modeling of heat conduction in glass coated with a thin film of SnS–Cu_xS [48T], extensive testing of vacuum glazings [59T], use of automated window shades [71T], modeling of transmittance and absorptance of coated or tinted glass [74T], use of the DOE 2 simulation program to model thermal and optical properties [77T], insulating technology for window perimeters [79T] and modeling of solar gain [84T]. Study of other exterior surfaces focuses on storage walls [68T, 82T, 83T], analysis of heat transfer through walls [47T, 49T–52T, 54T–56T, 75T], floors [66T], passive floor collector systems [53T] and roofs [58T]. A method to measure the overall heat transfer coefficient for building envelopes is presented in [70T]. Analyses of building energy loads include a correlation to determine thermal delay based on transient heat transfer analysis [51T], a method to estimate solar absorptance in rooms [57T], use of neural networks [67T], prediction of airflow patterns in large enclosures [61T] and evaluation of whole building simulation programs [62T, 63T, 69T]. Reference [73T] presents an experimental analysis of six houses with either active solar collectors or trombe walls. Reference [76T] derived expressions for hourly energy use for commonly used HVAC systems. Models to predict sol temperature [64T, 65T] may be useful in the evaluation of earth-to-air heat exchange systems which are the subject of [60T, 72T, 80T, 81T]. Reference [78T] discusses general rules in the design of passive solar buildings.

20.5. Water and space heating

Studies of water heating systems which combine collection and storage in a single component include comparison of measured and simulated performance for an evacuated tube collector [94T]; an algorithm to estimate solar gain of the same collector [96T]; an analytical expression for a flat-plate design [100T] and a model of a collector with salt hydrate as the storage medium [99T]. Other approaches to minimize the number of components or improve performance are the thermosyphon two-phase system [97T] and a heat pipe solar collector [90T]. An alternate approach is use of an air collector with rock bed storage and an air-to-water heat exchanger [87T]. The benefits of Second Law analysis to evaluate system performance is discussed in [93T]. Reference [92T] investigates flow distribution. For multi-family use, [98T] studied a central collector with storage for each family.

Most studies of residential space heating are numerical simulations [85T, 86T, 88T, 89T]. The benefits of a variable versus constant air flow rate through the collector and rock storage bed are examined in [85T]. Reference [86T] presents an optimization of an air heater with rock storage for use in Delhi. Transient analysis of an absorber made of tubes filled with sensible heat storage material indicate an improvement in system performance compared to the conventional flat plate system [88T]. Reference [89T] solves the transient heat conduction problem in a region with a cylindrical heat source. Preliminary data from an operating 91 m^2 inter-seasonal storage heating system are presented in [95T]. Energy storage in encapsulated phase change material is used with a solar assisted heat pump to heat a building in Turkey [91T]. No papers on swimming pool heaters appeared.

20.6. Space cooling and refrigeration

A literature search of alternate low cost absorbates for absorption cooling identifies a solution of two parts lithium chloride and one part zinc chloride as useful in reducing pumping power, decreasing the risk of solidification and improving solubility in open-cycle systems [102T]. Reference [104T] suggests a modification to the conventional open regenerator. Analysis of a system in which the desiccant is first heated in a glazed collector and then evaporated in an unglazed section provides the ratio of surface areas providing the highest regeneration efficiency. Reference [108T] suggests the use of a heat exchanger to recover heat from the outlet solution. The best performance of a rotary dehumidifier for a desiccant system is predicted for materials with an isotherm shape with a separation factor of 0.07 [109T]. Reference [103T] modeled the diffusion resistance inside desiccant particles and found a quartic concentration profile gives slightly lower error that a parabolic profile. Numerical analysis of a liquid desiccant system in which the cooled air does not contact the desiccant evaluates the effect of efficiency of the desiccant tower [106T]. The effects of regeneration temperature and ambient temperature on cooling capacity and COP are studied in [110T]. Reference [111T] analyzed a two-stage refrigeration system to determine the optimum interstage pressure. Reference [105T] simulated operation of an absorption heat pump in Ankara. Cooling potential of earth-to-air heat exchangers [107T] and nocturnal use of collectors to cool water [101T] are studied.

20.7. Storage

Most papers address the use of storage as part of a system and are thus discussed by application in the appropriate section. See for example papers [85T–89T, 94T, 95T, 98T] in the section on water and space heating. The only paper specific to sensible heat storage is a Second Law analysis of liquid storage with a hot gas source [113T].

Use of latent heat storage as part of a heating system are discussed in the section on water and space heating [91T] and [99T]. Reference [116T] investigates of the use of a mixture of Glauber's salt and stearic acid in an attempt to increase storage capacity while releasing energy at constant temperature. The best combination is 60% salt and 40% acid. Gong and Mujundak propose a similar concept for space applications (see section Applications in Space) [137T]. Reference [114T] presents First and Second Law analyses of phase-change storage in series with heat engines. Heat transfer and pressure drop correlations were developed for cold storage with tetradecane oil in a heat exchanger [115T].

20.8. Stills and desalination

Most papers address methods of improving technical performance. References [117T, 118T, 121T, 122T] model convectional solar stills. Reference [118T] suggests an alternative to the Dunkle model for prediction of evaporation rate, while [121T] looked at the effect of orientation in Delhi. Reference [122T] predicts performance of a still coupled with flat plate collectors; [119T] considers instabilities in a system which exploits the difference in vapor pressure of seawater and fresh water for desalination; [120T] conducts an experimental and analytical study of production of concentrated ethanol in a fermentation process.

20.9. Ponds

The number of papers in this category is small with only two small-scale experimental studies. Reference [124T] presents thermal performance data of fresh water shallow ponds for water heating and [125T] discusses the use of fertilizer to establish a salinity gradient in a small tank. Numerical work includes studies of mixing [123T, 127T], effect of turbidity on penetration of solar radiation [128T] and effect of ground reflectivity on thermal losses [126T].

20.10. Cooking and drying

Only three papers appeared in this category. A practical guide to use of a box cooler in Egypt is given by [130T]. A numerical study of a concentrating cooker points out the advantage of use of a glass-sided oven over a conventional bare receiver pot [129T]. The only paper on solar drying suggests an experimental procedure to test dryers indoors [131T].

20.11. Solar chemistry

The interest in photocatalytic detoxification has waned compared to last year. Only [132T] considers this application. The numerical study is an optimization of size and operating conditions. Production of hydrogen from a low temperature (1000K) splitting of water [134T] and electrolysis [133T] are analyzed.

20.12. Applications in space

Power generation in space is the subject of [135T–137T, 142T]. A thermodynamic analysis [135T] and presentation of design guidelines for components in combined and binary cycles [136T] are presented for the Freedom Space Station. Theoretical analysis of space-based gas stirling provides expressions for optimum power and efficiency [137T]. Development of a ground-based demonstration of a Brayton engine and the importance of life time and cold start requirements are discussed [142T]. An optical model of a cylindrical receiver and parabolic concentrator yields the distribution of flux in a zero atmosphere [139T].

Tests of a hybrid Kapton–Mylar insulation blanket for the Saturn spacecraft Cassini show that it can survive the expected temperatures [141T]. Modeling of phase change storage materials shows that use of a composite material may reduce the variation in output temperature [138T]. Numerical analysis of an orbital concentrator designed to melt large diameter crystals addresses uniformity of melt pattern [140T].

21. Plasma heat transfer and magnetohydrodynamics

21.1. Plasma modeling and diagnostics

Characterization of non-equilibrium plasma conditions dominated the plasma characterization literature. Two papers look at the thermodynamics of multitemperature systems [5U, 10U], with Giordano and Capitelli concentrating on discussion of a two-temperature Saha equation. Chen and Eddy introduce a formalism using the chemical affinity for description of reacting flows. The mixing of a plasma jet with the surrounding cold gas is modeled by Huang et al. [12U] using a two-fluid turbulence model and the results show the relatively long persistence of the high density cold gas bubbles in the plasma stream. A numerical model describing an air plasma expansion shows the differences between the translational and the vibrational temperatures and the chemical composition, and experimental data have been used to validate the code [13U]. A similar flow situation is characterized theoretically and experimentally by Fasoulas et al. [9U], who present results of a model describing a nitrogen plasma jet in a windtunnel and compare them with various experimental measurements. Two papers are concerned with mass spectrometric measurements of composition profiles in nitrogen–oxygen plasma flows [3U, 17U] and the dominant reactions are evaluated. In an experimental study of a helium plasma in an expanding arcjet, a population inversion has been observed and explained by a collisional radiative model [2U]. The influence of slip flow boundary conditions is calculated for low density, fully developed plasma flow with thin grey radiation transfer assumed [1U]. Radiation transfer calculations using the method of partial characteristics are presented for SF_6 and SF_6–Cu arcs in nozzle flow circuit breaker conditions [14U, 15U] and the mechanisms for continuum emission in an inductively coupled argon plasma have been investigated by emission measurements during the plasma decay [7U]. Emission spectroscopic measurements show deviation from LTE in the cathode region of argon arcs due to overpopulation of neutral ground state atoms near the region of high temperature gradients [11U].

A simplified method for calculating the impedance of an induction plasma has been obtained by assuming an exponential distribution of the current density in the reactor [6U], and a new model of a surface wave discharge is presented by Azarenkov et al. [4U]. Experimental probe measurements on a pulsed coaxial plasma gun are compared with an analytical solution for electron temperatures and densities in [18U]. Fluctuations of arc voltage and of Cu line emission intensity from eroded electrode material have been used to describe arc instabilities in a magnetically rotated arc and small amounts of CO contamination have been found to enhance stability [8U].

21.2. Plasma–solid interaction

Arc-electrode effects are discussed in two papers, one of which presents a model for the transition from atmospheric pressure micro-arcs to a single high current arc, finding that this transition depends on the cathode temperature and workfunction [22U]. The other paper describes results of heat flux measurements to the electrodes during the transition of a diffuse vacuum arc to one in which significant anode evaporation occurs [24U]. Analytic expressions for the influence of evaporation from a particle on the drag force acting on this particle in a rarefied plasma flow are presented in [20U]. A numerical model of particle–plasma interaction is derived for an inductively coupled plasma torch used for powder synthesis [23U].

Plasmas generated by laser–solid interaction are described in several papers. One paper describes the recombination dynamics of a laser production tantalum plasma [25U] and two papers present experimental results of supercritical density plasmas generated by very short (femtosecond) high power laser pulses irradiating quartz [26U] and aluminium [21U]. The plasma generated by a 1.5 MA pulse discharge initiated by a wire explosion is described in [19U] and the effects of the metal vapor radiation on the discharge are demonstrated.

21.3. Specific plasma applications

Modeling of specific plasma processes is growing. A model of an arc melting furnace for waste processing includes the convective motion of the molten waste, and conclusions reached are that short high current arcs are preferred for improved energy deposition and mixing [39U]. Similar conclusions are reached from a model for an electric arc furnace for metal production [40U]. An experimental study has investigated the efficiency of a titanium arc melting furnace [38U] and the plasma carburization of steel has been shown to be crucially dependent on the inlet position of the methane gas and the adequate mixing of the methane with the plasma gas [36U]. The addition of argon flow to a plasma fluidized bed reactor for calcium carbide production has resulted in increased conversion efficiencies at reduced temperature operation [43U]. A one-dimensional unified plasma spray model has been developed including the plasma flow, the particle heating region and the substrate, and resulting correlations of plasma operating parameters with coating properties showed good agreement with experimental observations [30U]. Various diagnostics have been used to compare atmospheric pressure and low pressure plasma spray processes, including spectroscopy and Langmuir probes for determining ion and electron temperatures and densities and plasma velocity [34U].

Two papers discuss the effects of plasma formation and radiation absorption during laser beam welding and the beneficial effects of shield gas flow [28U, 42U]. A model of the keyhole plasma welding process including phase change under the influence of a moving heat source is presented by Nehad [37U], and the change of fume formation when the welding arc changes from globular to spray mode is discussed in [33U]. Eight different models for electric discharge machining are compared with respect to their predictions of matching performance and computation times [32U].

The thermal performance of a membrane X-ray mask exposed to a plasma has been investigated in [35U]. Heat transfer measurements during the arc discharge process for titanium nitride deposition have been performed with biased probes, and steady state and transient temperature values are reported in [41U]. Deposition of metal oxides in a similar process is described in [27U] including the filters used for avoiding deposition of macroparticles. Two papers deal with heat transfer in electric launchers, e.g. electrode erosion in an electrothermal launcher, showing the benefits of using a coating or tungsten alloy electrodes [29U], or the effects of pressure on plasma heating of the propellants [31U].

21.4. Magnetohydrodynamics

A 2-D model of a fully developed MHD flow in a rectangular duct has been used to study effects of cracks in the insulating layer, and a strong effect of crack location on pressure drop has been found [53U]. Expressions for skin friction and heat transfer for flow of a small Prandtl number fluid over a semi-infinite plate have been obtained with an integral approach [50U]. A numerical experiment with a time-dependent 2-D model has been carried out to optimize the performance of a plasma vane MHD generator [46U]. Effects of the magnetic field on convection in a porous medium have been modeled for mixed convection along a vertical plate using a new transformation approach [45U], and for natural convection in a tilted porous enclosure [44U]. An analytical solution predicting temperature and heat flux profiles in a 2-D enclosure has been formulated and an analogy with a flow through a porous medium has been found [52U].

A survey of theoretical and experimental efforts on solar assisted liquid metal MHD power generation devices is presented in [48U]. Liquid metal blankets for fusion reactors are discussed in [47U, 49U, 51U]. Kirillov et al. [49U] present an overview of MHD and heat transfer phenomena. Reimann et al. [51U] present results of Li flow experiments, while Branover et al. [47U] review heat transfer enhancement through turbulence in MHD flow of mercury.

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