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Heat transfer: a review of 1998 literature

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1. Introduction

The present review is designed to encompass the English language heat transfer papers published in 1998. The papers have been categorized into a number of sub-fields. While being exhaustive, some selection is necessary. Besides reviewing the journal articles of 1998, we also briefly mention important conferences and meetings on heat transfer and related fields, major awards to heat transfer researchers and also books on heat transfer published during the year.

An ASME meeting on Turbulent Heat Transfer held in Manchester, England on 31 May–5 June covered shear flows, separation and reattachment and LES in industrial applications. The 43rd Gas Turbine and Aeroengine Congress, User's Symposium and Exhibition 'Turbo Expo–Land, Sea and Air 1998' was held in Stockholm, Sweden on 2–5 June. Topics covered included external heat transfer, internal air systems and seals, film cooling, and internal heat transfer. An International Symposium on Heat and Mass Transfer in Biomedical and Medical Engineering was organized by the International Centre for Heat and Mass Transfer in Kupadasy, Turkey on 8–12 June. Sessions covered therapeutic processes, mass transfer and cryobiology. The Joint AIAA/ASME Thermophysics and Heat Transfer Conference held in Albuquerque, USA on 15–18 June had sessions on computational aerothermodynamics, microscale heat transfer, and heat transfer in porous media. The Fifth International Conference on Advanced Computational Methods was held in Cracow, Poland on 17–19 June. Sessions covered conduction, natural and forced convection, change of phase, and heat exchangers. The 11th International Heat Transfer Conference was held on 23–28 August in Kyongju, Korea. Topics covered included condensation and direct contact gas/liquid heat transfer, external forced convection, heat transfer augmentation, natural convection, radiation and combustion, numerical techniques and modeling and two-phase flow with and without phase change. The 8th International Symposium on Flow Visualization on 1–4 September in Sorrento, Italy covered combustion, droplet breakup, multiphase flows, and natural convection. The 1998 International Mechanical Engineering Congress and Exposition (IMECE) was held in Anaheim, USA on 15–20 November. The Heat Transfer Division of the ASME held sessions on impingement and film cooling in turbomachinery, inverse and optimization problems in heat transfer, and jet impingement heat transfer.

Awards and Honors: The 1998 Heat Transfer Memorial Awards were presented to Dr. Amir Faghri (Art) and Dr. James V. Beck (Science). The Max Jakob Award (1997) was presented to Dr. John Howell for his contributions to the development and application of theoretical methods for predicting radiative heat transfer in participating media. The Donald Q Kern award instituted by the AIChE was presented to Dr. Ephraim Sparrow for his significant contributions in translating results of research into useful technological applications. The Luikov award instituted by the ICHMT was awarded to Dr. Arthur Bergles for his pioneering scholarly contributions to heat transfer, in particular, in the field of enhanced heat transfer.

Some interesting highlights of this year's review are: Gas turbine engine cooling continues to be the primary motivation for heat transfer studies on rotating disks and channels. Work on numerical methods includes heat conduction (both direct and inverse problems), melting/freezing, convection and diffusion, and fluid flow techniques. Methods are aimed at the treatment of complex geometry, improved accuracy, and robustness. Papers on heat transfer applications address prediction of temperature fields in electronic devices, loss of coolant accidents in nuclear reactors, building envelopes, and issues in manufacturing.

Books on heat transfer published during 1998 include:

Advanced Computational Methods in Heat Transfer V:
A.J. Nowak, M. Zerroukat, R. Bialecki, C.A. Brebbia (Editors),
Computational Mechanics Inc.

Advances in Heat and Mass Transfer in Biotechnology
S. Clegg (Editor)
ASME Press

Advances in Heat Transfer (Vol. 31)
J.P. Hartnett, T.F. Irvine, Y.I.Cho, G.A. Greene
Academic Press

Analytical methods in Conduction Heat Transfer
Glen E. Myers
AMCHT Publications

Annual Review of Heat Transfer
Begell House

Biotransport: Heat and Mass Transfer in Living Systems
Kenneth R. Diller (Editor)
Annals of the New York Academy of Sciences

Biological Process Engineering: An Analogical Approach to Fluid Flow, Heat Transfer and Mass Transfer Applied to Biological Systems
Arthur T Johnson
Wiley

Computer Simulations in Compact Heat Exchangers (Developments in Heat Transfer, Volume 1)
Bengt Sunden (Editor), M. Faghri (Editor)
Computational Mechanics Inc.

Computer Technology of Solving Problems in Gasdynamics
V.I. Timoshenko, Natalia K. Shveyeva
Begell House

Convection in Porous Media
Donald A. Nield
Springer-Verlag

Fundamentals of Heat and Mass Transfer and Interactive Heat Transfer
F.P. Incropera, D.P. De Witt
Wiley

Handbook of Heat Transfer
W.M. Rohsenow, J.P. Hartnett, Y.I. Cho
McGraw-Hill

Heat and Mass Transfer
Karl Stephan, H.D. Baehr
Springer-Verlag

Heat and Mass Transfer in Building Services Design
Keith Moss
Routledge Publishers

Heat Transfer
Anthony F. Mills
Prentice-Hall

Heat Transfer With Applications
Kirk D. Hagen
Prentice-Hall

Heat Transfer: A Practical Approach
Yunus A. Cengel
McGraw-Hill

The Heat Transfer Problem Solver (Problem Solvers)
James R. Ogden
Staff of Research and Education Association

Heat and Mass Transfer Australasia 1996: Proceedings of the Sixth Australasian Heat and Mass Transfer Conference
E. Leonardi, C.V. Madhusudana
Begell House

Heat Transfer Augmentation in Turbulent Flows
A. Pedisius, A. Slanciauskas
Begell House

Heat Transfer Essentials
Latif M. Jiji
Begell House

Heat Transfer Fundamentals for Metal Casting
D.R.R. Poirier, G.H. Geiger (editors)
The Minerals, Metals and Materials Society

Heat Transfer in Electronic Packages
Rao Tummala, Eugene J. Rymaszewski, Alan G. Klopfenstein
InterThom

Introduction to Convective Heat Transfer Analysis
P.H. Oosthuizen, David Naylor
McGraw-Hill

Modelling of Heat Transfer Phenomena, Vol. 2
B. Sunden, M. Faghri (editors)
Computational Mechanics

An Introduction to Convective Heat Transfer Analysis
David Naylor, Patrick H. Oosthuizen
McGraw-Hill

Mathematics of Heat Transfer
A.S. Wood
Oxford University Press

Methods for Inverse Heat Conduction
Dinh Nho Hao
Peter Lang Publishing

Operation of Counterflow Regenerators
B.S. Baclic, Gordan D. Dragutinovic
Computational Mechanics

Schaum's Outline of Theory and Problems of Heat Transfer
Donald R. Pitts, Leighton E. Sissom (Contributor)
McGraw-Hill

Schaum's Outline of Heat Transfer
J.P. Holman
McGraw-Hill

Thermal Vibrational Convection
D.V. Lyubimov, G. Z. Gershuni
Wiley

Transport Phenomena in Materials Processing
D.R. Poirier, G.H. Geiger
The Minerals, Metals and Materials Society

2. Conduction

Numerous subtopics related to heat conduction are reviewed in this subcategory. These are categorized as: contact conductance/contact resistance; composites and/or heterogeneous media; thermal waves and non-classical effects, microscale heat transport, and laser or pulse heating; heat conduction in fins, tubes and solids; modeling, analytic and numerical techniques; experimental and/or comparative studies; thermomechanical problems; inverse problems and design studies; flow effects, change of phase and process studies; microelectronic heat transfer; and miscellaneous and special applications.

2.1. Contact conduction/contact resistance

The thermal contact resistance at the interface of double tubes assembled by plastic deformation is described in the study by Bourouga and Bandon [1A]. That involving study of bolted joints is described in Mantelli and Yovanovich [2A] and contact conductance of elastomeric gaskets by Mirmira et al. [3A]. The thermal resistance of two solids in contact through a cylindrical joint and between polished surfaces is described in Refs. [4A–6A].

2.2. Composite and/or heterogeneous media

The effects of thermal insulation behavior of a multi-layer orthotropic cylinder [7A], an exact solution derivation in composite material and application to inverse problems [8A], the estimation of transfer matrix of a thermoelastic acoustic disturbance induced in a layered medium [9A], the kinetics of thermal instability in the presence of a nonuniform temperature distribution composite [10A], the the modeling of damage effect on heat transfer in time-dependent nonhomogeneous solids [11A], and the heat conduction in multilayer spherical products by transfer functions [12A] appear in this subcategory.

2.3. Thermal waves and nonclassical effects, microscale heat transport, and laser or pulse heating

The various subtopics in this subcategory encompass numerous studies related to heat waves and the respective solutions as described in Refs. [13A, 14A, 17A, 21A, 22A, 24A, 25A, 28A, 29A]; microscale thermal transport as described in Refs. [18A, 19A, 23A, 27A], and laser or pulse heating applications as described in Refs. [15A, 16A, 20A, 26A, 30A].

2.4. Fins, tubes and arbitrary geometries

The conjugate heat transfer of a plate fin and triangular fin in a second grade fluid flow [31A, 32A], conduction heat transfer from confined spheres [33A], and the application of Taylor transformation to optimize rectangular fins with variable thermal parameters and prediction of thermal stresses in isotropic annular fins [34A, 35A] appear in the literature.

2.5. Modeling, analytic and numerical techniques

As always, this subcategory almost always receives a wide variety of activity across a broad range of application areas employing closed form derivations, finite element, finite difference, boundary element techniques and the like. The contributions range from new developments in numerical techniques to the application of existing techniques to new problems and/or studies of heat transfer in materials and structures [36A–48A].

2.6. Experimental and/or comparative studies

The experimental and theoretical analysis of thermohydrodynamic seizure [49A], an experimental study and numerical simulation of the injection stretch/blow molding process [50A], and experimental and analytic study of periodic heat conduction in a multilayer medium [51A] appear in this subcategory.

2.7. Thermomechanical problems

The studies involving thermomechanical problems including coupled heat transfer and thermal stresses in high t-c thin film superconductor devices [52A], thermal optimization in transient thermoelasticity using response surface approximations [53A], and the effects of thermal gradient and residual strsses in thermal barrier coating fracture [54A].

2.8. Inverse problems and design studies

Various inverse problems encompassing heat conduction, prediction of heat flux of an m42 percussion primer, solution of an inverse problem subjected to specification of energies, inverse determination of steady heat convection coefficient distributions, a new space marching method, and the solution of temperature and thermal stress fields appear in Refs. [55A–60A].

2.9. Flow effects

The study of chaotic heat transfer in a periodic two-dimensional flow is described in [61A] and the classification of one- dimensional steady state two-phase geothermal flows including permeability variations is described in [62A].

2.10. Microelectronic heat transfer

The modeling of rarefied gas heat conduction between wafer and susceptor [63A] and a tool for a compact dynamic thermal model generation [64A] appear in the literature.

2.11. Miscellaneous studies and special applications

A wide variety of applications and studies involving conduction heat transfer with particular emphasis on specialized applications appears in Refs. [65A–78A].

3. Boundary layers and external flows

Papers on boundary layers and external flows for 1998 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 film and interfacial effects, flows with special fluid types and property effects, and flows with reactions.

3.1. External effects

Papers which focus on external effects document the influence of streamwise thermal gradient effects [2B, 5B, 9B, 13B], buoyancy effects [1B, 14B], flows influenced by embedded vortices [10B, 11B], flows modified by variable density effects [3B, 4B, 8B, 15B], and flows influenced by electric and magnetic fields [6B, 12B]. The effects of thermal gradients included one in which a revised Blasius solution was developed [13B] and two applied to a stretching surface [5B, 9B]. One of the buoyancy- influenced flows showed how suction modified the mixed-convection heat transfer coefficient [1B] while another showed the effect of orientation of a Rankine vortex embedded in the boundary layer [11B] and a third noted a three-fold increase in heat transfer for a situation where a vortex tube interacted with a sphere [10B]. Acoustic enhancement was applied to incineration [15B] while rapid compression in a piston–cylinder arrangement was addressed in [8B, 3B]. The influence of an electric field on suspended drops was discussed in [6B], showing how the drops were deformed, while in [12B], convective roll cells, as influenced by a magnetic fields were analyzed to develop stability curves. The stability of boundary layer flows as influenced by centripetal forces due to curvature was experimentally documented while the pressure gradients, which usually accompany curvature in duct flows, were removed [7B].

3.2. Geometric effects

One paper in this category dealt with a slip-stick boundary condition on a sphere [48B], another with non-stokes flow over particles in turbulent flow [47B], a third on a particle of irregular shape [28B], and a fourth on the heat and mass transfer from a droplet [43B]. A mathematical model was presented for the analysis of a granulating column [37B].

Several papers dealt with cylinders. In one, mixed-convection heat transfer was evaluated for slender cylinders [22B] and in two [34B, 17B] numerical solutions were presented for flow over cylinders in cross-flow; on one, both compressible and incompressible flows were modeled [34B] whereas in another [17B] the effects of angle of inclination of an elliptical tube were investigated. Finally, a model was developed for the turbulent heat flux in the wake of a cylinder [52B].

On stagnation flow, one paper showed equations derived to estimate stagnation region heat transfer [36B], another modified the unsteadiness at the edge of the near-wall viscous region to account for the free-stream turbulence, level and scale [53B], a third computed heat transfer under an impinging jet [19B], a fourth discussed heat transfer under an array of orthogonal jets [32B], and a fifth quantified augmentation via impingement on a rough surface [25B].

Papers which focused on roughness included two on the effects of non-homogeneous roughness [39B, 45B], another considering a liquid film surface roughness [49B], and a fourth presenting the effect on turbulence spectra when the roughness is grass [35B]. Finally, a paper was presented which discusses the effects of isolated roughness regions on transition over the Shuttle Orbiter surface [20B].

Ribbed surfaces were discussed in [51B, 26B, 33B, 38B]. In [51B], a transient measurement technique was presented; in [33B], ribs were applied to narrow channels; and in [38B], perforated ribs were compared to solid ribs. Winglets were applied to enhance heat transfer in [29B] and the general topic of enhancement was addressed in [31B].

Several papers considered representations of computer elements on boards [24B, 41B, 46B]. In one [24B], heated cubes were placed downstream of a roughness element and in another [46B], direct liquid cooling was applied to flush-mounted and protruding elements.

A rather large number of papers were dedicated to turbine flows [16B, 21B, 18B, 30B, 23B, 27B, 44B]. In one, roughness effects were quantified, some cases were with the surface coated with grit, some were with tumbled grit, and some were polished [16B]. In a second, the combined effects of roughness and elevated free stream turbulence intensity were discussed [21B]. In a third, a model was presented for capturing the effect of roughness [30B]. In one paper, transition was addressed, where cases of various freestream turbulence intensity were presented along with a model for capturing the high turbulence effect [18B]. The effect of isentropic work extraction in the unsteady flow downstream of a turbine was measured [23B]. Simultaneous temperature and velocity measurements were presented for a radial-inflow turbine [27B] and the flow in face seals was documented in [44B].

Several entries in this category were on a large scale. Paper [40B] discussed the effects of boundary layer thinning in off-shore flow, with the effects of its associated change in roughness, whereas [42B] discussed heat losses, mantle overturn, and gas evolution in the earth's mantle.

Finally, for this category, a paper was presented on the effects on pressure drop and heat transfer coefficient of non-uniform plate length in a heat exchanger [50B].

3.3. Compressibility and high-speed flow effects

In this category, there was a review of analytical solutions for compressible unsteady boundary layers [55B] and a solution for compressible flow past a cylinder [57B]. Under hypersonic flow, one paper examined turbulence models and made a proposal for use in heat transfer predictions [59B], another used a generalized reference enthalpy formulation to identify a similitude error which is stated to be important in transition zones [62B], a third showed the effects of angle of attack for a blunt- nosed, ramped, flat plate [58B], the fourth applied a stability term which is significant at high Knudsen numbers [63B], and the fifth discussed non-equilibrium effects in molecular nitrogen [54B]. High-speed flow of liquid monopropellant from a nozzle was addressed, with focus on evaluation of numerical schemes [61B] and compressible, low-speed flow in an electrical furnace was discussed, including the effects of back diffusion [56B]. Finally, experimental data taken for flow characterization of a wind tunnel for high speed flight testing were used to propose a thermochemical model which involves vibration–dissociation–recombination coupling [60B].

3.4. Analysis and modeling

The modeling of vorticity at the wall and the influence of the no-slip boundary condition for flow past a 2D cylinder were presented in [89B]. The effect of heat transfer from the wall on the stability of flames in burners was addressed in [92B]. Thermophoresis effects on boundary layer flows were analyzed by including the effect of particle deposition on the wall [71B]. The method of characteristics was applied to an underexpanded free jet flow with vibrational non-equilibrium for application to shock tubes [87B]. The quest for invariant descriptors in heat transfer was the topic of [86B]. Techniques from the literature were reviewed. The effect of heat transfer on transition of flow past a cylinder was quantified in terms of an effective Reynolds number [73B].

Several papers dealt with integral techniques [72B, 78B, 74B]. One [72B] is an analysis of laminar, mixed convection between vertical parallel plates, another is for uniformly-heated ducts [78B], and a third [74B] used the Chilton–Colburn analogy to compute flow with longitudinal pressure gradients.

Two papers dealt with conjugate heat transfer; one [94B], for flow past a flat plate while the other [93B] was to model two-row, finned tubes.

Several papers addressed atmospheric boundary layers. In two [64B, 65B], mass transfer from soil to the atmosphere was considered using data of land-surface fluxes; in a third, heat and mass transfer from a cooled surface were addressed [66B]; and, in a two-part paper [67B, 75B], the effects of strong concentration gradients on viscosity were quantified.

A series of papers was presented on boundary layer transition. One specifically addressed laminar-to-turbulent transition in gas turbine flows [70B], another [68B] presented data which shows the discrete levels of turbulence intensity in a boundary layer flow undergoing transition to turbulence, and a third [88B] addressed transition from turbulent natural to turbulent forced convection.

Several papers in this category focused on coherent structures. In one [98B], the effects of coherent structures on the wall region were discussed, another [97B] addressed the modeling of coherent structures for heat and mass transfer computation, a third discussed the modeling of temperature streaks using a statistical model [84B], a fourth addressed the coherency between heat flux and temperature fluctuations in 3D boundary layers [83B], and the last observed thermal signatures of free-surface waves to describe a surface renewal mechanism and its effects on heat flux [96B].

Turbulence modeling remains popular. New steps this year addressed the modeling of wallward flow in the viscous sublayer [69B], used an improved Louis scheme to allow different roughness lengths for the momentum and heat transfer in atmospheric boundary layers [81B], modeled diffusivity in grid-generated turbulence [82B], modified a mixing length model for strong heating effects [85B], changed a near-wall model to increase computational speed in flows with buoyancy effects [95B], captured vortex–wall interactions for computing unsteady heat flux rates from the wall [90B], used Lagrangian stochastic models for application to stratified flows [77B], improved low-Reynolds-number, k–epsilon models for computation of near-wall heat transfer coefficients [79B], and, compared the performance of an RNG model against DNS computations for wall shear flows [80B].

Two papers focused on DNS. The first addressed particle flows in isotropic turbulence using a pseudo-spectral method [91B] and the other applied DNS to a turbulent boundary layer solution [76B].

3.5. Unsteady effects

Flows in this category included one on unsteady, conjugate heat transfer for a particle over a range of Peclet number from 0 to 10 [99B], and another on heat transfer from a cylinder in a low-turbulence freestream [102B]. One paper addressed pulsatile flow past a cylinder, for application to Stirling engine regenerators [100B], while another studied an impulsively-started flat plate in which the effects of mass diffusion on the velocity profile were quantified [101B].

3.6. Films and interfacial effects

Papers with strong emphasis on interfacial effects included three on droplets [109B, 104B, 103B]. In the first, droplet evaporation in a turbulent flow was computed [109B], another was concerned with sea sprays [104B], while the third focused on droplet formation [103B].

In [108B], gas bubble nucleation during rapid decompression was analyzed. Heat and mass transfer in wall films were studied [110B] with application to fuel separation. A need for modeling improvements was noted. Models for gas–liquid interface heat transfer were tested and recommended in [107B].

Two papers discussed Marangoni effects on heat and mass transfer. In one, critical Reynolds numbers were found, with their corresponding wave numbers [106B]. In the second, a dimensionless number for thermocapillary-driven flow was introduced [105B].

3.7. Effects of fluid type or fluid properties

Several papers in this category considered the behavior of viscoelastic and power-law fluids. An analytical solution was presented for laminar flows [123B]. Flows over stretching sheets were analyzed in [112B, 114B, 115B, 119B–121B]. In [114B] the effect of suction was analyzed and in [112B], reversal of heat flow with position from the leading edge was shown.

Temperature-dependent viscosity was included in a numerical solution of a combined free- and forced-convection flow [117B]. An exact solution for heat transfer with a low-Prandtl-number fluid flowing over plates and cylinders [118B] was presented and the effects of approaching the thermodynamic critical state on thermal resistance was shown [122B].

Heat transfer to a ferrofluid in the presence of a magnetic field was numerically computed [111B]; in doing so, it was found that the effect of the magnetic field was to reduce heat transfer.

Two papers were given in which the nature of a particle-laden flow was stressed. In one [116B], the study was on the effect of homogeneous turbulence whereas the second showed the importance of Brownian motion [113B].

3.8. Flows with reactions

Several papers were with emphasis on combustion. In one [126B], kinetic theory was applied to plane jet flows, and the effects of turbulent transport were included. In another [125B] temperature dissipation in jet flames was analyzed looking at the interaction between chemistry and turbulence. Another paper presented the interaction of two jets askew to one another in a furnace to note that substantial cooling was effected by heat exchange with the furnace [128B]. The combustion of coal in a shock tube was experimentally investigated where it was noted that there was very little heat transfer to particles in the homogeneous combustion zone [127B]. Burning on a vertical surface with cross-flow was analyzed, looking at various fuel types and various Reynolds numbers [124B]. The spread of a flame on a thermally-thick surface was studied where various models were considered and the effects of several parameters were shown [130B]. Finally, low-NO_x regenerative burners were numerically considered for use in a slab reheat furnace [129B]. They were shown to perform favorably.

4. Channel flows

4.1. Straight-walled ducts

The geometrical simplicity of straight-walled ducts has proven itself to be a reliable test configuration for numerical simulation/validation and for the consideration of boundary and initial conditions through experimental inquiry. A critical review appeared in the literature [12C] concerning the heat transfer characteristics of supercritical CO_2 in tube flow. Direct numerical simulations of turbulent channel flows were conducted with linear spanwise mean temperature gradients [8C] and with low to medium-high Prandtl number fluids [6C]. Turbulent channel flows were also modeled using k–ε techniques. A rectangular duct having an aspect ratio of 8:1 was examined using a combined numerical and experimental approach [14C]; various low Reynolds number models were compared in turbulent pipe flow [5C]; thermal transport mechanisms in turbulent gas flows were also studied using k–ε modeling for viscosity and kinetic energy [19C]. The transition from very low to high Reynolds numbers in the developing zone of a channel was examined using a control-volume-based finite element method [3C]. A finite element code was used for the analysis of mixed-convection in a horizontal channel heated from the side walls [17C]. A closed form expression for the fully developed velocity, temperature and concentration profiles in a vertical channel were found in the limit of infinite aspect ratio [9C]. An analytical solution for skin friction and heat transfer was undertaken for compressible flow by an extension of the law-of-the-wall to account for compressibility [4C]. A weakly nonlinear theory was used to investigate fully developed Poiseuille flow subject to constant heat flux [20C]. Heat transfer in vertical channels of a gas-discharge apparatus, experiencing mixed-convection, was approximated using integral relations [15C]. The three-dimensional temperature field in the thermal entrance region of a rectangular duct was solved analytically [18C]. Variable property effects were accounted for in one study of forced turbulent convection to water in a pipe [1C]. The entrance region of thin vertical tubes was studied to determine the effect of axial diffusion on laminar heat transfer [10C]; thick walled tubes with isothermal outer surfaces were examined when subjected to high-pressure flows of gas and liquid [2C]. A mathematical model was used to predict the wicking height in a capillary as affected by heat transfer in the thin film region [7C]. The viscous layer in a strongly-heated gas flow was measured to guide the development of advanced turbulence models [16C]. A parallel-plate electrochemical flow cell was studied, having opposing and aiding flow; relationships between heat and mass transfer rates were considered [11C]. The heat transfer enhancement in the entrance region of a vertical channel was also investigated [13C].

4.2. Microchannel flow

While microchannel heat transfer studies are still relatively sparse in the literature, this trend will undoubtedly change in the near future. The use of the Brinkman number for correlating convective heat transfer in microchannels was reexamined [25C]; a dimensionless geometric parameter was also proposed. An experimental study of single-phase forced convection of water in circular microchannels led to the development of generalized correlations for the Nusselt number [21C]. The use of a transmission window employing microchannel cooling indicates the dramatic impact that microchannel heat transfer can have on beam flux [26C]. The flow of gas in a microchannel was studied using nitrogen and helium as working fluids; the slip flow regime was examined [22C]. The effects of aspect ratio and Knudsen number on microscale flow in rectangular channels was addressed in the slip flow regime [24C]. Compressibility and heat transfer effects were considered in the flow of gas in a microtube [23C].

4.3. Irregular geometries

Several straight-walled ducts with triangular, semicircular, trapezoidal, concentric annular and grooved walls were examined in the literature. The effect of surface roughness on forced convective heat transfer in a triangular duct was studied experimentally; nondimensional expressions for heat transfer were developed [34C]. Surface roughness was also examined in triangular ducts together with the impact of duct wall angle [36C]. The fully-developed laminar flow in a semi-circular duct was investigated to evaluate the effects of temperature-dependent viscosity [33C]. A three-dimensional numerical simulation of a trapezoidal cross-sectioned duct with wavy walls was undertaken, using a finite volume technique with a nonstaggered grid [38C]. The logarithmic wall laws of mean axial velocity and temperature were obtained for the heated inner wall of a vertical concentric annular channel [39C]. Laminar flow was studied in the entrance region of a eccentric annuli using a finite-difference algorithm [30C]. A direct numerical simulation demonstrating heat transfer augmentation in a transversely grooved channel was undertaken in the Reynolds number range of 140–2000 [31C]. Channel flows experiencing wavy walls were studied by a number of investigators. A linear stability analysis of the two-dimensional flow in a wavy-walled channel was conducted; both symmetric and sinuous channel configurations were considered [29C]. A study of Tollmien Schlichting waves in a wavy channel was done; instability was found to set in at a Reynolds number of approximately 90 [27C]. A combined numerical simulation and flow visualization study of a sinusoidal wavy wall was done for very viscous liquids [37C]. The turbulent flow and heat transfer in a periodically converging–diverging channel was simulated using a two-equation k–ε model [32C]. The heat transfer characteristics from ethylene glycol and water solutions was examined in spirally indented tubes; Prandtl number effects were discussed [35C]. Non-uniform blowing and suction were studied numerically in the porous wall of a circular tube with constant heat flux [28C].

4.4. Finned and profiled ducts

The inevitable tradeoffs between heat transfer augmentation and pressure drop make duct profiling a rich design problem. The broad class of so-called ribbed ducts, was considered in a large number of studies. Experiments were performed to examine the water cooling of protruding heated elements mounted in a rectangular channel [45C]. Heat transfer enhancement was studied in compact heat exchangers using holographic interferometry [50C]; holographic interferometry was also used to investigate rectangular perforated ribs [52C] and solid ribs [54C] of different heights in a rectangular passage. The effect of rib open area was also studied in a rectangular duct [53C]. Rib turbulators were used with bleed holes to achieve heat transfer enhancement in a two-pass square channel [44C]. The two-dimensional forced convective heat transfer between plates with flush mounted heat sources, used to simulate electronic cooling, was studied numerically [63C]. Steamwise periodic rods were used to augment heat transfer in laminar flow between parallel plates [64C]. Slit and solid ribs mounted on a single wall of a rectangular duct were studied experimentally; a combined flow visualization and quantitative study was conducted [48C]. A series of studies was undertaken in one group to measure the heat transfer characteristics in ducts: low-aspect-ratio ribs were examined in one study [58C]; staggered 45-degree rib geometries were tested in a square channel [59C]; measurements of heat transfer and friction factors were made in square and trapezoidal ducts with ribs on all walls [60C]. The effect of periodic ribs was investigated in a straight cooling channel [56C]. Heat transfer measurements were made in a rib-roughened passage; comparisons were made between rounded and sharp cornered ribs [51C]. Internally ribbed turbine blade passages were studied and the influence of cylindrical vortex generators was considered [46C]. Secondary flow patterns, pressure drop and heat transfer were investigated in a rib-roughened rectangular channel [55C]. An open channel flow was studied with protruding heaters on one side [42C]. A horizonal printed-circuit board with lifted electronic components was studied; the role of vertical protrusion on heat transfer was considered [49C]. The heat transfer enhancement caused by an array of cubic fins was examined in a narrow channel [41C]. Three-dimensional calculations were performed for thermally and hydrodynamically developed laminar flow in a finned oval tube [40C]. One paper investigated the unsteady flow and heat transfer from rectangular sources with and without an included plate in the channel [62C]; a related paper considered the impact of vortex shedding on the heat transfer performance [61C]. A combined analytical and numerical study of the heat transfer in a three-dimensional corrugated channel was undertaken in the Reynolds number range up to 250 [57C]. The effects of baffle size, perforation, and orientation were considered on the heat transfer in a rectangular channel [43C]. An experimental study was done to study the developing turbulent mixed convection in a horizontal tube with strip-type heaters [47C].

4.5. Channel flows with periodic motion and secondary flow

A theoretical analysis was undertaken of the periodic laminar flow and heat transfer in a tube, as would be found, for instance, in Stirling engines [75C]. The unsteady conjugate heat transfer was studied for flow in a circular tube with periodically varying inlet temperature [80C]. Sinusoidally varying inlet temperature was examined theoretically in a parallel-plate channel [69C]. Pulsating channel flows were investigated for channels with grooved walls [78C] and with isolated heated electronic components [74C]. The transient thermal response of flow to various pressure pulses was studied using the semi-direct variation method of Kantorovich [71C]. The unsteady motion and heat transfer in Stirling and pulse-type refrigerators was studied [67C]. The fluid-thermal characteristics of the flow at the intake manifold of a spark-ignition engine was examined [66C]. The pulsatile flow through a smooth constriction with area reductions of 25%, 50% and 75% was investigated, experiments were conducted over the physiologically relevant mean Reynolds number of 600 [65C]. Thermoacoustic streaming was examined in a plane parallel resonant channel; it was shown that the conjugate wall–fluid coupling is crucial in yielding the large time-averaged axial temperature gradients that can be induced in the channel [70C]. The buoyancy-induced secondary motion in the entrance region of a horizontal straight tube was studied; air and water flows were considered [79C]. Combined flow visualization and temperature measurements were made to investigate the effect of aspect ratio on the characteristics of longitudinal vortex flow at the bottom of a horizontal rectangular duct [68C]. Secondary motion established by the imbalance between centripetal acceleration and pressure gradient was considered in a number of studies. The transitional flow and heat transfer occurring at high Dean number were studied [77C]. A numerical study considered the three-dimensional turbulent flow and heat transfer in the entrance region of a curved pipe [76C]. Mild curvature was studied at Dean numbers from 300 to 750; a variety of laminar-to-turbulent transition flow behavior was observed [73C]. The transient behavior in a helically coiled pipe with pulsatile fully developed turbulent flow was examined experimentally [72C].

4.6. Multiphase channel flow

The turbulent heat transfer characteristics of ultra-fine metallic oxide particles suspended in water was investigated experimentally [86C]. The deposition of small particles due to thermophoretic effects was studied using the direct numerical simulation of turbulent channel flow [89C]. Infrared thermography of an electrically heated tube was used to investigate the heat transfer in intermittent air–water flows; both horizontal [81C] and upward inclined tubes were considered [82C]. The role of surfactant additives in reducing drag and heat transfer were studied [87C, 88C]. The flow of fluids near their critical point was studied in the entrance region of a vertical tube [85C]. Buoyancy effects on the enhancement of heat transfer using an electrohydrodynamic technique was investigated numerically [84C]. Analytical and numerical tools were used to study the hydromagnetic slip flow in an inclined channel; boundary conditions for velocity and temperature were addressed [83C].

4.7. Non-Newtonian flow

The non-Newtonian flow in a rectangular duct with constant temperature walls was studied; three-dimensional mixed convection was considered [91C]. The flows of inelastic, shear-thinning and shear-thickening fluids were studied in shallow channels [95C]. Experiments were carried out in a Sulzer SMX static mixer for the heat transfer of Newtonian and non-Newtonian fluids [94C]. The heat transfer and pressure drop in heat exchanger passages were considered for non-Newtonian fluids [93C]. Research was done to evaluate the effect of fluid motion on the conductivity of non-Newtonian fluid, as well as the effect of shear-rate-dependence on heat transfer [92C]. A numerical study was performed to evaluate the following effects: the temperature dependence of viscosity; shear thinning properties; and buoyancy-induced secondary flow [90C].

4.8. Miscellaneous channel flow

A handful of papers did not fit well into the primary categories for channel flows. A fully-developed packed-bed flow was simulated numerically; a two-dimensional model incorporated the effects of Raschig ring packing on the Ergun equation [104C]. Drop tower experimental results were presented of the flow characteristics of gas–liquid two-phase annular flow under microgravity [99C]. Mass transfer coefficients were measured to deduce heat transfer rates from particles suspended in a vertical holding tube [98C]. An analytical model was developed to examine aspects of rate-controlled seizure in an unloaded journal bearing [103C]. The thermal performance of three different regenerator matrices was considered; general formulae for the heat transfer rates as a function of flow channeling were developed [96C]. The hydrodynamics and heat transfer under conditions of flow of conducting liquid in a flat channel in a transverse magnetic field were studied [101C]. An investigation was carried out to evaluate the optimal number of tubes in a dry-expansion evaporator; focus was on changes occurring when R22 is replaced with R407C [100C]. Measurements were made of the heat transfer in a severely outgassed tube bank [97C]. The heat transfer for rectangular solar air heater ducts packed with wire mess screens was studied [105C]. An analytical study of the heat and mass transfer through a parallel-plate channel with recycle was presented [102C].

5. Separated flows

Flow past bluff objects and obstructions leads to flow separation and often reattachment. Heat transfer measurements were made downstream of a surface mounted two-dimensional rib; complementary computational results were also reported [1D]. One report used the three-dimensional incompressible Boussinesq equations in primative variable form to examine the flow past a heated and cooled sphere [13D]. A summary of numerical studies of laminar flow past heated circular cylinders was provided [12D]. Buoyancy flow past a circular cylinder was studied; the flow field and temperature distribution was predicted using a novel finite volume algorithm [18D]. The flow and heat transfer over a three-dimensional spherical object positioned in a pipe was presented [17D]. An analytical solution was obtained for the forced convective heat transfer from a circular cylinder at low Reynolds numbers [11D]. The oscillatory flow and heat transfer in a channel with tandem transverse vortex generators was examined numerically [20D]. A combined experimental and numerical study was conducted to study the flow pattern and heat transfer through a tube bank [14D]. Pulsatile flow past two heated blocks positioned in a channel were investigated numerically [9D]. Experiments were also conducted on the forced convective heat transfer over tandem blocks in a channel [4D]. Single and multiple heated objects in a channel were studied [23D, 24D]. The generalized integral transform technique was used to study the thermal boundary layer equations for flow past two-dimensional and axisymmetric bodies [2D]. A numerical study was used to investigate the heat transfer from two-dimensional, steady, laminar flow in a channel with two ribs [3D]. A control-volume-based finite-difference method was used to study the turbulent flow downstream of a backward facing step with jet discharge perpendicular to the main flow [22D]. A new scaling procedure is used to study the velocity and temperature turbulent boundary layer during separation [5D]. The important interaction between buoyancy and inertia forces was studied in a combined numerical and experimental study of the flow past a backward facing step [10D]. Swirling flow experiencing pipe divergence is studied experimentally; a divergence angle of 7 degrees was considered [6D]. The viscous shock layer was examined using a numerical simulation of two-dimensional nonequilibrium supersonic flow past axisymmetric blunt bodies with catalytic surfaces [8D]. An asymptotic non-adiabatic triple-deck model was used to study the supersonic and hypersonic shock laminar boundary layer interaction [7D]. Experiments were performed to investigate the shock-wave turbulent-boundary-layer interaction caused by a blunt swept fin-plate configuration [19D]; experiments were also conducted to study the shock boundary layer interaction using oil flow visualization and simultaneous measurements of fluctuating wall pressure [21D]. The thermal time constant in a fiber-filled loudspeaker was studied [15D]. The convective heat transfer associated with the streamwise development of counterswirling coflowing jets confined within a tube was studied [16D].

6. Porous media

The literature on heat and mass transfer in porous media continues to expand. Along with the traditional applications to packed and fluidized beds and insulation systems, an increase of activity on volume averaging techniques, property determinations, and dispersed phase has occurred. A number of studies have focused on various aspects of transport within porous surfaces, and we present a special section below on this topic.

A goodly number of very fundamental studies this past year have addressed issues of overarching applicability to all of the categories of this review. The equations and requisite thermal boundary conditions for radiative transfer in translucent porous media has been extensively reviewed by Siegel [17DP, 18DP]. The complex process of non-isothermal/isothermal liquid composite molding has been described via macroscopic constitutive relations derived from a microscopic analysis of the representative elementary volume [11DP].

Witaker and co-workers have developed the constraints associated with solute transport in a chemically and mechanically heterogeneous medium and thereby have determined when a large scale average velocity, a single absorption isotherm and a large-scale dispersion tensor apply [15DP]. A related study uses the Witaker volume averaging technique to develop models for diffusion and reaction in bio-films [20DP]. The heat transfer boundary condition at the interface between a porous medium and homogenous fluid was conceptualized as a flux jump condition also based on volume averaging techniques [12DP], and the general equations for non-Newtonian flows in porous media were rigorously developed within the framework of volume averaging [3DP].

The description of heat transfer in dispersed porous media has been reformulated in terms of a new dimensionless parameter that takes into account the disperse phase aerodynamic resistance [9DP]. A more specialized study considers the description of friction and heat transfer via power law relationships for laminar cross flow in sparse periodic cylinder arrays [6DP].

Multiphase flows with heat transfer have been investigated from several perspectives. A classification has been developed for one-dimensional steady geothermal flows with permeability variations related to saturation [21DP]. A set of nonlinear governing equations has also been developed for coupled heat, moisture and air transfer in deformable unsaturated media including heat of wetting, heat sink effects owing to thermal expansion, phase change, and compressibility [22DP]. Basic studies of capillary porous media have reported a derivation of the governing equations that include the physical characteristics of the medium [16DP] and a model for heat transfer in capillary pumped grooves [14DP]. The stability of vapor–liquid counter flow was shown to be stable with respect to small disturbances in the saturation field and the pressure field was shown to be asymptotically stable for all choices of thermal boundary conditions [13DP]. For coupled heat and mass transfer processes in a deforming matrix, a multi-frontal algorithm that employs the effective stress concept, latent heat release, capillary pressure, and convective heat transfer has been developed [19DP].

A kinetic theory for dense gases was applied to the analysis of heat transfer in granular flows [10DP]. Flow-induced kinetic diffusion in a rotating granular beds was investigated with a focus on the several flow regimes that can exist in the bed [1DP]. Fundamental data on gas-to-solid mass transfer coefficients in a rotating bed were measured, and the effects of baffles to produce a non-rolling bed were investigated [4DP].

Convective heat transfer to solid particles passing through a heated tube bundle was analyzed numerically [5DP]. An analysis of the thermal aspects of grinding via a two-temperature model for the grit and fluid was reported [2DP].

A dynamic equation of state has been developed for the solid–liquid interface for a liquid-saturated medium undergoing single-phase mass transfer and freezing–expansion at the phase front [7DP, 8DP].

6.1. Property determination

Research on determining the thermophysical properties of porous media continues with a focus on the effective thermal conductivity of saturated systems. An overall review of the scalar and transport equations obtained via the volume-averaging approach discusses non-local, linear and non-linear effective thermal and fluid properties [36DP]. Use of temperature at the microscale level has been used to model the volume-averaged effective thermal conductivity in two-dimensional anisotropic systems [30DP]. An experimental and theoretical study of a radial flow packed-bed reactor indicates that a two-equation and homogeneous model yield values of effective thermal conductivity that are in reasonable agreement only at low Reynolds numbers [28DP].

Work is underway on the relation between the internal structure, or geometry, of the porous matrix and predicted and measured properties. Light scattering in aerogels has been used to derive data on anisotropy, large pore fraction, induced stress, inhomogenieties and microstructure [29DP]. A geometric model using a random resistance network theory and parametric statistics has been used to model the thermal conductivity of snow and to link predicted values to micro-structural quantities [23DP]. The radial thermal conductivity in blown-through catalyst supports with gas motion has been measured as a function geometrical parameters and estimates are provided for heat transfer from the catalyst [35DP]. Measurements of thermal conductivity with a complete uncertainty analysis are reported for compacted metal hydrides via the comparative method [31DP]. The growth and heat transfer of deposited slag and ash were measured to provide estimates of internal ash temperature and effective thermal conductivity [26DP]. Related work deals with the connection of ash microstructure and chemistry to transport properties [24DP].

Adsorption in activated carbon in constant molar flow rate was measured at low pressure to determine the apparent diffusivity and reveal that combined pore and surface diffusion adequately explains the controlling mass transport mechanism [34DP]. An improved general model of the compaction in a porous medium was developed by applying elasto-plasticity to determine the effective stress and horizontal deformation [32DP]. The accoustic properties of saturated sporous media were modeled taking into account the effects of viscosity, interia and heat transfer [25DP]. The potential for spalling of either fully or partially saturated porous medium exposed to radiant surface heating has been shown to depend on effective thermal conductivity, saturation, and permeability [27DP]. The temperature dependence of the overall diffusion of nitrogen, argon, and oxygen through porous platinum was measured for 300–1000 K [33DP].

6.2. External flow and heat transfer

A variety of analytical and numerical techniques have been applied successfully to a range of heat/mass transfer problem for external surfaces. Complex variable methods via conformal mapping have been introduced for two-dimensional systems at low Prandtl number and arbitrary Peclet number [44DP]. The boundary layer equations for heat transfer in Darcy flow have been solved via the so-called Keller box method, and results compare well with a more traditional Runge–Kuttta scheme [39DP]. The Keller box method has also been applied to the coupled convection–radiation problem for non-Darcy free convection of a dissipative non-gray gas past a vertical flat plate [58DP] and to coupled heat and mass transfer in mixed convection on a vertical plate and cylinder imbedded in a saturated medium [63DP, 64DP]. Non-similarity methods have been applied to determine heat transfer in mixed convection from a horizontal surface with a variable surface heat flux [42DP]. Integral methods and Prandtl's analogy have been applied successfully to predict Nusselt numbers for a vertical plate in free convection at large Rayleigh number [55DP]. A two-parameter perturbation analysis for radiative effects on natural convection has been applied to flat surfaces and plume flows [51DP].

External flow and heat transfer past imbedded surfaces with mass flow (blowing or suction) have received attention. The fundamental problem of laminar Darcy flow past a transpired surface has been solved for the case of variable wall temperature [62DP]. A related study concerns MHD flows in a porous medium with a periodic suction velocity at the wall [47DP].

Enhanced heat transfer in streaming flow (low Reynolds number) past a permeable sphere wherein the radial surface flow is Darcian has been determined analytically for Prandtl numbers of order unity [61DP]. This problem is extended to cylinders with radial seepage that are embedded in a saturated medium [40DP]. The effects of suction and blowing on heat transfer in two-dimensional MHD Hiemenz flow through a porous medium have been numerically determined, and the effects of the surface velocity on local Nusselt numbers have been determined [65DP].

Free convection from heated surfaces facing upward and downward in an infinite saturated medium has been investigated numerically to reveal the details for the velocity and temperature fields [37DP, 38DP]. Analytical and numerical solutions at large Rayleigh number in free convection on a constant flux plate show that anisotropy in the medium can have a significant effect on heat transfer rates [60DP]. Similarity solutions for free convection driven by an exothermic chemical reaction were obtained via similarity methods for a vertical plate [50DP, 54DP]. The instability of buoyant boundary layers in a type of wedge flow are shown to depend strongly on the outer flow field [56DP].

Mixed convection, with viscous dissipation and thermal dispersion effects included, has been investigated via a seers solution for aiding and opposing flows [52DP]. Non-similarity methods have been applied for hydromagnetic mixed convection on a vertical plate to determine the skin friction and heat transfer coefficients [41DP] and to non-Darcy mixed convection from a horizontal surface with a variable surface temperature [43DP]. A non-similar boundary layer solution for mixed convection of a power-law fluid on vertical [45DP] and horizontal [46DP] plates.

Heat transfer measurements have been reported for a vertical surface and a horizontal cylinder embedded in a vibrating porous layer [59DP]. Double diffusive problems for natural and mixed convection from imbedded surfaces have also received some attention and re-examination [53DP, 49DP, 48DP]. An exact solution for the effects of visco-elastic flow with heat transfer and heat generation in a porous medium over a stretching sheet has been determined for both prescribed surface temperature and heat flux [57DP].

6.3. Packed and fluidized beds

Several papers have appeared this past year that have focused on the fundamentals of fluid flow, heat transfer, and mass transfer in packed and fluidized beds. The characterization of bed properties, flow structure, and controlling physical parameters have received attention as well.

Heat transfer data from a well characterized experimental study of a single-blow transient in a packed bed yield some definitive information on heat transfer and pressure drop [104DP]. The effect of temperature-dependent thermophysical properties on a fixed bed containing heat transfer tubes was seen mainly through velocity profiles as they are affected by the wall cooled and wall heated cases [80DP, 81DP]. A numerical investigation of a packed bed of eight spherical particles was conducted to determine wall heat transfer coefficients and the radial effective thermal conductivity [81DP]. The analysis of unsteady conjugate heat transfer from a single particle in a multi-particle system showed that the prediction of heat transfer is strongly affected by thermal conductivity and heat capacity ratios [78DP]. Numerical analysis of the fully coupled conduction–convection–radiation problem in a packed bed of small diameter silicon fibers in laminar flow shows that heat transfer enhancement occurs largely via the radiation [83DP]. A two-equation energy model and a general momentum equation were used to model transient heat transfer in compressible flow in a packed bed [67DP]. Heat transfer to water flowing through a rigid bed comprising sintered mono-dispersed metal fibers has been measured, and an increase of critical heat flux over that for pool boiling is measured [85DP]. A numerical study for non-Darcy forced convection in a power law fluid with constant temperature heating determined the effects of particle diameter and the power-law index on convective coefficients. [72DP]. A theoretical study of heat and mass transfer in a zeolite bed during water desorption tested the assumption of local thermal equilibrium [84DP].

The characterization of flow in packed beds has been carried out experimentally for intermediate Reynolds numbers (∼100–400) for air [86DP] and for liquids [76DP]. Measurements of the effects of buoyancy on flow at high pressure call into question the usual plug flow assumption [69DP]. Wall effects on pressure drop in an annular bed were modeled by a multi-zone flow model that produced good agreement with measurements [101DP]. The spreading of thin viscous films over complex surfaces has been shown to represent the flow from a drip point over an ordered packed bed [99DP]. An experimental study to determine the influence of tube and particle diameters on heat transfer in a wall-heated bed has shown that the ratio of the tube-to-particle diameter is the controlling design parameter [73DP]. Theoretical work shows bubble growth and dynamics depends on particle size distribution [77DP].

Models of packed bed rotary heat exchangers have been developed to account for axial heat dispersion and longitudinal matrix conduction [88DP]. as well as the various compactness of the matrix [87DP]. Combined mode heat transfer in soil with a bulk water flow has been obtained analytically with results being in good agreement with field data [96DP]. Energy storage in packed beds using either sensible heat storage materials or phase-change materials was modeled and validated with laboratory experiments [66DP, 98DP, 106DP].

Fluidization regimes in air–glass bead beds have been experimentally identified via statistical analysis of fluctuating temperatures within the bed [95DP, 102DP]. Cluster motion and particle-convective heat transfer at the wall of a circulating fluidized bed have been determined using a novel infrared imaging techniques [89DP]. Several studies report measurements of wall-to-bed heat transfer coefficients, local pressure fluctuations, and instantaneous temperature measurement [100DP, 82DP, 92DP, 97DP, 74DP, 75DP]. Data from a hydrodynamically scaled fluid bed have been used to predict particle residence time and heat transfer rates [91DP].

Heat transfer in a fluid bed combustor was successfully predicted with a bubble assemblage model that accounted for inter-phase heat transfer and thermal radiation to the wall [93DP].

The effects of flow distributing grates and packing on pressure and heat transfer in a fluidized bed have been reported for various hydrodynamic regimes [68DP]. Design parameters have been developed for water-cooled distributors for fluidized bed [105DP]. Fluidized bed membrane reforming has been proposed as an improvement over steam reforming for its economic and overall thermodynamic advantages [94DP].

Experimental and numerical studies of coupled heat and mass transfer in packed beds have been reported. Experiments were run on a cross-current absorber, and results were compared to predictions obtained with commercially available software [103DP]. Oberg and Goswami reported experiments on a packed bed, liquid desiccant dehumidifier including a comparison to a numerical model [90DP]. Experiments also show that optimal heat–mass transfer reactors can be constructed of copper coated, compressed metal hydride powders [79DP]. Related studies report the use of micro-encapsulated phase change materials to enhance heat transfer in gas fluidized beds [71DP] and the effects of particle thermal time constants on fluidized bed convective coefficients [70DP].

6.4. Layers, enclosures and annuli

Research on heat transfer in a variety of enclosure types included both fundamental and technology-specific topics during the past year. The more standard problem of determining the effects of boundary conditions on steady and transient convection has given way to investigations focusing on the structural, thermo-diffusion, thermo-osmosis, and thermal-filtration characteristics of the matrix and the enclosure, or layer [135DP, 120DP, 110DP, 107DP, 145DP, 125DP]. The growth of porous substrates, such as encountered in soldering, has been modeled with a diffusion-reaction mechanism and an implicit numerical scheme to track layer growth. An optimization scheme assigns length scales for diffusion smaller than the smallest macroscopic flow path, optimizes flow geometry, and thereby deduces both the structural features of the flow and the important heat transfer relations [132DP].

Convection in rotating porous systems was analyzed to determine coriolis effects for stability in layers heated from below and for weak, non-linear convection [141DP]. Bifurcations in supercritical rotating convection and the nature of multiple solutions of the time-dependent Darcy–Boussinesq equation were analyzed via a truncated Galerkin method [143DP]. A rotating Hele–Shaw cell and a thermo-sensitive liquid crystal tracer are discussed [142DP].

A two-temperature model for heat transfer in insulation materials has been developed and applied to insulating materials [144DP]. A simple semi-implicit time stepping procedure has been successfully applied to buoyancy driven flow in a square cavity [134DP]. A two-field model for natural convection in an annulus in which porosity varies near the wall and fluid properties are temperature-dependent was reported [115DP]. Non-Darcy effects have been considered for saturated media in which either a density maximum exists in the fluid or a volume-averaged heat source exists [111DP, 114DP, 124DP].

Double-diffusive effects that lead to layering have been experimentally simulated with a rigid porous matrix saturated with a salt-water solution and heated from below [138DP]. Vertical and inclined enclosures with binary and non-Newtonian fluids were also investigated [118DP, 117DP, 130DP, 131DP].

Transient natural convection in a vertical saturated cylinder opened at the extremities and heated on the wall was numerically determined using the extended Darcy model and a two-temperature model [139DP]. Oscillating forced flow and heat transfer in porous heat exchangers were investigated experimentally [128DP] and numerically [122DP]. The transient entrance region problem for the forced convection in a porous annulus was investigated for the case of fully developed entering flow [109DP].

Forced flow in channels and pipes either partially or completely filled with a porous medium was the topic of several investigations. Analytical studies for the couette flow in a partially porous channel [126DP] and in a fully porous channel [127DP, 112DP] were reported. Turbulent convection in a fully porous channel was calculated using direct numerical simulation and an ad hoc model of the structure of matrix [140DP]. A numerical analysis was reported for flow and heat transfer in the entrance region of pipe partially filled with a porous material [108DP]. Open channel flow with a porous medium was used to model the edge effect in liquid composites molding [119DP]. Unidirectional, adiabatic infiltration with solidification and re-melting in a porous medium were modeled numerically to produce profiles of solute, temperature and solid volume fraction [123DP].

Predictions using a non-Darcian formulation of axial and radial temperature distributions in forced flow in cylinder were in good agreement with experiments [121DP]. The use of open-celled foam in the form of heated slender cylinders as compact heat exchangers in a channel was analyzed for constant wall temperature and a range of geometries [129DP]. Flow and heat transfer were investigated for a porous medium supporting a lateral temperature gradient and vertical throughflow [133DP, 137DP].

Three specialized studies in 1998 merit mention.

Volumetric heat transfer coefficients for cellular ceramics fixed to the wall in forced convection were measured via the single-blow transient technique [116DP]. Fluid flow and heat transfer were analyzed numerically for channel flow with intermittent heated porous blocks on the wall [113DP]. A experimental study by the same group considered enhancement of laminar forced convection from heated non-porous blocks at the wall by insertion of a porous material between them [136DP].

6.5. Coupled heat and mass transfer

Several very fundamental studies of coupled heat and mass transfer have appeared on the effect of structural inhomogeneity in the solid matrix. These include the effects of thermal gradients, reactive chemical transport, evaporation–condensation processes, and cooling produced by the dissociation of the matrix under high heat flux boundary conditions [148DP, 173DP, 194DP, 151DP, 171DP]. The deterioration of a brittle matrix due to freezing and thawing was experimentally studied and modeled at the micropore level [162DP].

A screening procedure based on transport attributes has been developed for synthesizing isothermal multiphase reactors at the early stages of chemical process design [169DP]. A homogenization of the pore- and macro-levels has been proposed as the basis for modeling heat transfer in a non-saturated porous medium [147DP], and a related study presents two- dimensional numerical solutions for transport in non-saturated soils [175DP]. Devolitization of an individual coal particle, such as is found in a fluid bed reactor, has been modeled as a function of heating rate and particle diameter [184DP]. Heat and mass transfer both within and exterior to a porous catalyst particle were modeled using recently obtained kinetics for methane–steam reforming [172DP].

A review of mechanisms and analytical models for enhanced vapor-diffusion has been presented [161DP] that demonstrates the need for additional experimental work to sharpen future analysis. A related group of studies has addressed various aspects of the drying problem, including capillary phenomena, steam injection, effects of boundary conditions, flow instability, and all aspects of phase change including freezing and sublimation [193DP, 155DP, 153DP, 152DP, 174DP, 178DP, 186DP–190DP, 157DP, 149DP]. A porous media model has been applied to the continuous casting process to take account of the formation of columnar dendrites in the mushy zone [191DP].

Packed bed bio-reactors, essentially mass exchangers with reaction, have been modeled in connection with solid state fermentation processes. Two-dimensional models have been developed and successfully validated against laboratory scale reactors for prescribed bed characteristics and air saturation [182DP, 160DP]. The pyrolysis of biomass particles in a fluid bed has been modeled to investigate the coupling of the kinetic and transport processes [183DP]. Related studies include the simulation of a carbon-packed bed for the absorption of toluene and experiments on the nitridation of palletized silicon at 1200°C [181DP, 167DP].

Stationary porous channels and flat moving beds have been investigated both experimentally and analytically. Experiments using sintered copper for a two-phase heat sink suggest applications to the cooling of micorelectronics [180DP]. The fluid–solid mechanics of a moving bed of particles with a counterblow of a chemically reacting gas was experimentally investigated in the context of a model development for iron ore reduction [159DP]. Coupled heat and vapor flow in a flat plate heat pipe was analyzed using a pseudo three-dimensional analytical model [196DP].

Research on combustion in porous media has addressed gas–solid reactions as possible thermochemical heat pumps [177DP] and the effects of multimode heat transfer and kinetics on the evaporation and combustion of liquid fuel droplets in an inert matrix [176DP]. One study has aimed at developing a general model for non-equilmolar transient reactions in porous pellets [179DP], and others treat the role of a reaction-dependent matrix structure during the combustion process [146DP, 154DP, 156DP, 168DP]. Catalytic and non-catalytic porous burners under stagnation flow conditions, localized heating conditions, and with radiative heat transport were the subject of modeling efforts [158DP, 195DP, 170DP, 163DP, 192DP].

Studies related to fires have continued to focus on the coupled heat and mass transfer problem under applied heat fluxes at the boundary [164DP–166DP]. Some new work on diffusive self-heating of wet combustible materials has appeared [150DP]. The effect of moisture level on coupled heat and mass transfer in hollow cavities driven by an external fire was modeled to deduce an overall mass exchange coefficient [185DP].

6.6. Porous surfaces

During the past year, the literature has developed a subset of articles on transport to and within porous surfaces. Phase change heat transfer is clearly one area that is receiving more attention. Studies range from the augmentation of condensation [199DP] to flow and boiling studies [202DP–205DP].

Heat and mass transfer effects of porous inserts down stream of a rearward facing step [200DP] and the effects of pyrolysis on a carbon surface [198DP] were modeled and analyzed numerically. Heat transfer with particle deposition during a vapor deposition process was studied experimentally to characterize surface effects on temperatures and mass transfer rates [197DP]. An analytical model of the conjugate heat–mass transfer problem for a porous wall was developed in connection with modeling the transpiration cooling process [201DP].

7. Experimental methods

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

Several authors described the design or characterization of heat flux gauges [6E, 10E, 18E]. Infrared imaging technology was used to measure the surface heat flux or heat transfer coefficient [15E, 16E, 19E]. Thin film technology [9E] was used to measure the heat transfer coefficient in a film cooling application and atmospheric boundary layer heat flux was estimated from a single-level measurement of air temperature [23E]. Local heat transfer coefficients were determined using liquid crystals [2E, 3E] and the color change caused by chemisorption of a dye was used for local mass transfer determination [13E, 14E]. Other measurements of local heat transfer included optical methods such as laser speckle photography [12E] and a quantitative Schlieren technique [22E]. The design and construction of guarded hot plate and cold plate instruments was given [4E, 5E]. Several authors reported on the use of various types of calorimeters [1E, 7E, 8E, 11E, 17E, 20E, 21E].

7.2. Temperature measurements

Discussions of novel thermocouple applications were presented [34E, 37E]. Thin film heat flux gauge technology was used to construct a fast response total temperature probe [24E, 25E]. An application of laser reflectance thermometry [32E] was given. Magnetic resonance imaging was used to measure the temperature distribution within potatoes [33E] and may be a useful method to measure the temperature in human tissue noninvasively [27E]. Image processing in Mach–Zehnder interferometry [35E] and limitations in holographic interferometry [39E] were described. Three papers that describe the use of liquid crystals for temperature measurement were published [26E, 31E, 36E]. Various aspects of the use of infrared thermometry were discussed [28–30E, 38E].

7.3. Velocity and flow measurements

Liquid crystals were used to visualize the thermal wakes from small heated spots [40E] to determine flow direction. A new particle image velocimetry technique was developed for studying the flow near an evaporating film [42E]. The use of a pulsed wire method [41E] and signal correction for nonisothermal flows [44E] were given for hot wire anemometry. An array of five hot film sensors mounted on a hemispherical tip was used to determine the three components of local flow velocity [46E]. Flow visualization using an electronic speckle pattern interferometer [48E] and a holographic interferometer were described [43E]. The characterization of two types of total flow meters was given [45E, 47E].

7.4. Thermophysical property measurements

Methods to measure the thermal conductivity in solid methane [52E] and in low thermal conductivity materials [51E] were presented. A heat pulse method was described for measuring the thermal properties of soils [49E], and a sensitivity analysis was presented for measurements of thermal diffusivity using a periodic method [53E]. A novel method to measure thermal and optical properties simultaneously during sintering was given [55E]. A method to measure the index of refraction of a liquid was described that can be used to infer the composition of a liquid mixture [54E]. The diffusion coefficient of a binary liquid solution was determined using a transient concentration pulse [50E].

7.5. Miscellaneous methods

A novel data reduction procedure for transient heat transfer measurements [63E] and statistical design of inverse heat transfer problems [61E] were described. Several authors describe the use of infrared radiometers and IR sensors [56E–60E, 64E]. A solar pyranometer using a thermoresistive element is described [59E] and a photographic procedure to determine local mass transfer coefficients is demonstrated [62E].

8. Natural convection — internal flows

8.1. Fundamental studies

Fundamental studies of natural convection in internal flows span the analysis of the onset of flow to direct numerical simulation of the turbulent Rayleigh–Benard (R–B) problem. Perhaps for the first time, a benchmark problem has been defined for validating computational fluid dynamics codes. This problem is the cubical air-filled cavity, tilted at 0, 45 and 90°, with one pair of differently heated faces and the other faces having a linear temperature variation [7F].

The onset of flow in the R–B problem, the stability of mixed convection in a vertical channel, turbulence in the horizontal layer, and direct numerical simulation of turbulence have all received attention [3F, 2F, 8F, 5F]. The scaling laws for Nusselt-versus-Rayleigh number in the horizontal layer have also been investigated numerically, and a new generalization has been proposed [1F]. An upper bound on heat transport in R–B convection at moderately high Rayleigh number has been calculated via variational principles [10F].

Several studies report on the dynamics of double diffusive instabilities and flow intrusions in laterally heated layers [4F, 6F]. The limitation of boundary layer analysis for the heat surfaces is also demonstrated [9F].

8.2. Heat generating fluids

An interesting extension of the R–B problem to develop a parameterized model of the thermal evolution of the planets via a temperature-dependent viscosity with volumetric heat generation has been presented [13F]. On a more fundamental level, the heat transfer relation has been determined at low Rayleigh numbers for a flat layer with adiabatic horizontal boundaries and cooled end walls [12F]. Bolshov et al. [11F] have reported a semi-quantitative study of the Nusselt-versus-Rayleigh number relation with results being in good agreement with existing experiments.

8.3. Thermocapillary flows

Thermocapillary flows have received a good deal of attention within the context of microgravity and crystal growth applications. Work also continues on the floating half-zone convection problem and new results are presented for a three-dimensional unsteady simulation [22F]. The effect of tilt angle on the evaporation of a liquid film in a microgrooved channel has been determined via a perturbation technique up to the first order perturbation [17F]. One study has analyzed Marangoni effects on a liquid drop in an immiscible fluid with surface reaction, the spreading of drops on a liquid surface with surfactant, and the modified R–B problem with heat and mass transfer at the upper, shear free surface [23F]. Weakly non-linear Marangoni R–B convection in a layer with a uniform vertical magnetic field reveals the presence of a sub-critical region that is dependent on the magnitude of the impressed field [18F].

A linear stability analysis of thermocapillary instabilities in floating half-zone convection in a microgravity environment was compared to experiments to determine the effect of the liquid bridge volume and aspect ratio on the critical Marangoni number [15F]. Oscillatory instabilities appearing in a two-fluid layer via buoyancy have been studied numerically, and results suggest criteria for encapsulation of the low Prandtl number fluid and the role of Marangoni forces in suppressing oscillatory flow [24F]. The development of oscillatory instability in thermocapillary flow contained in a cylindrical column was found to depend on the deformation of the free surface and its subsequent effect on heat transfer in the hot-corner region [20F]. Induced multicellular thermocapillary flows in a dielectric droplet translating in dielectric fluid with an impressed electrical field were found to depend on the induced interfacial temperature distribution and may either enhance or decrease heat transfer to the droplet [21F].

In a somewhat specialized study of thermosolutal convection in a fluid layer, the existence of the surface tension effect is found to alter the evolution of the flow field and can either increase or decrease local heat and mass transfer coefficients [19F]. For a single component layer with two free surfaces, thermocapillary forces can produce stronger multicellular convection than for the case of one free surface [16F].

New experimental facilities have been developed in Japan to determine the thermocapillary velocity of drop migration in microgravity [25F]. Fundamental experimental studies have also been conducted on Marangoni R–B instability and convection with evaporation to reveal the flow mechanisms at the onset of convection [14F].

8.4. Enclosure heat transfer

Experimental studies for stratified fluids in rectangular domains presented correlations for heat transfer and new data on roll convection in high Prandtl number fluids and have investigated long-standing issues in wavenumber–heat flux characteristics [27F, 29F, 30F]. Experiments on the near-wall dynamics of flow in R–B convection at moderately high Rayleigh numbers suggest a heat transport model comprising a periodic array of two-dimensional plumes [47F]. Average heat transfer coefficients have been measured in R–B convection at low Prandtl number [51F].

Mixing of hot and cold fluids in a rectangular enclosure has been studied to determine both the details of temperature and velocity fields, as well as the relation between key dynamic parameters [34F, 41F]. The control of vorticity in R–B convection was approached via the use of Lagrange multipliers and the Pontryagin minimum principle [42F]. A comparison of turbulent diffusive transport in R–B convection and in internally heated layers showed that distinct correlations of Nusselt versus Rayleigh number apply for the two flows and suggest that different closure relations are needed for transport in time-averaged models [50F]. The effects of surface roughness with a characteristic length equal to the to thermal layer thickness have been found to alter the relation between the Nusselt and Rayleigh number [49F].

The presence of mixed boundary conditions on a square cavity leads to a sequence of Rayleigh numbers at which cellular flows of increasing frequency develop as the system traverses the steady to quasi-steady regimes of flow [37F]. Two-dimensional enclosures were investigated for the effect of tilt angle [33F], magnetic field [26F, 45F], thermally coupled walls [46F], unstable wall temperature distributions [35F], and double diffusion effects [43F, 36F, 48F]. When thermal boundary conditions are time-dependent, resonance between the induced flow and the period of wall fluctuations can be obtained with a related increase in mean Nusselt numbers [38F, 39F]. A two-dimensional analysis was applied to a cylinder heated on the vertical wall and cooled at the top to reveal tendencies toward roll flows with a preferred structure [40F].

Heat transfer correlations have been developed via experiments for a small heat source mounted on a rectangular surface and shown to be significantly different from the usual correlations for heated flat plates [44F]. For a series of parallel, interacting open-top cavities with multiple heat sources, numerically predicted heat transfer coefficients have been used to determine the effects of the several key parameters on heat transfer coefficients, especially wall conductivity [28F]. The characteristics of the buoyant plume rising from a finite source in a cavity have been experimentally studied and new regimes of flow and heat transfer have been suggested [32F].

Numerical studies have also been conducted for free convection in fluids continuing a suspension of fine particles such as dust. Thermo-rheological models were employed in one case. Major features of the flow fields and heat transfer coefficients have been presented [52F, 31F].

8.5. Vertical ducts and annuli

Turbulence in vertical cavities and annuli has been investigated numerically to determine overall heat transfer and turbulence budgets. With both direct numerical simulation (DNS) and k–ε methods, good agreement was found with available experiments [54F, 57F]. New experimental data for heat transfer and velocity fields in vertical annuli with local circumferential heating were reported [56F].

Transition from laminar to oscillatory flow was investigated via DNS to determine the contributions made by flow shear and buoyancy to the generation of fluctuating kinetic energy in the vertical annulus of radius ratio two [55F]. For an eccentric annulus with an open end, new results for developing heat transfer and flow field were presented [53F].

8.6. Horizontal cylinders and annuli

Time-dependent and turbulent flows were also a focal point of research on natural convection in horizontal cylinders and annuli. Numerical and experimental studies were reported on the existence of multiple flow regimes and their relation to a bifurcation in the solution [58F], on oscillatory flow and its transition to chaos [62F], on the effect of piecewise heating on the outer wall [63F]; and on flow structures in annuli with $Pr < 0.3$ [64F].

Additionally, a numerical study of convection in the horizontal annulus containing a micropolar fluid near its maximum density reported overall heat transfer coefficients [59F]. Special studies were conducted for the inclined annulus [60F] and for the annulus with multiple geometric perturbations on the inner cylinder [61F].

8.7. Mixed convection

A variety of flow geometries have been the focus of largely numerical studies of mixed convection, some of more fundamental importance than others. Developing flow in a horizontal concentric annulus with an adiabatic outer wall exhibits secondary flows that are mainly confined to the entry length [69F]. Buoyancy effects on heat transfer from a horizontal surface in a partially open enclosure can have a significant effect depending on the conditions imposed on the open surface [67F]. Several studies for vertical channels examine buoyancy effects on flow structure, viscous dissipation and heat transfer [74F, 70F, 73F, 66F, 65F, 68F].

A study of contaminant removal in a two-dimensional enclosure with one inlet and one outlet reveals that buoyancy can have a significant effect on removal time [72F]. A related study examines the heat transfer relations for a rectangular cavity that is both heated and ventilated from the side walls [71F].

8.8. Complex geometries

Several specialized flow geometries have been the focus of research this past year. A parametric study of a combined vertical and horizontal enclosure indicates that flow and heat transfer can be approximated by the processes within the vertical and horizontal subdomains [81F]. A numerical study of three-dimensional convection in a cube with one side open reports overall heat transfer coefficients for low Rayleigh numbers [84F].

Double diffusive convection in a v-shaped sump is characterized by thin boundary layers and differing gradients of solute and temperature for a general class of boundary conditions [79F]. Multi-cavity, or partitioned, enclosures have been the subject of several fully numerical studies addressing both free and mixed convection [78F, 85F, 82F]. Boundary conditions comprising multiple heat sources in parallel, interacting activities have been varied to produce an overall heat transfer correlation for such [75F].

A numerical investigation of natural convection in a horizontal rod bundle has produced heat transfer results that are in good agreement with experimental data [76F]. Heat transfer correlations were also obtained for a cooled cylinder in a rectangular cavity filled with water near the density maximum [83F] and for heating of a finite cylinder in a fluid well above the density maximum [77F]. Free convection in greenhouses heated by an array of heating pipes has been numerically determinedwith several internal geometrical factors being considered [80F].

8.9. Fires

Fundamental studies of heat transfer and fluid flow in fires has touched on the structure of a one-dimensional spray diffusion flame [88F] and the effective thermal conductivity during flame spread over a shallow sub-flash liquid fuel layer [87F]. A related study examines the radiant heat flux to a body engulfed in a pool fire [90F].

Basic investigations that have significance to human safety include a simulation of turbulence of indoor gas flow in the presence of an ignition source [91F]. The problem of flashover has been investigated to determine the interacting influences of material properties, room configuration and ventilation [86F]. The thermal properties of flame resistant fabrics in a flash fire have been investigated for to develop thermal design guidelines for fabric design [92F]. Peacock et al. have presented a discussion of the overall modeling strategies and issues involved with developing fire models [89F].

8.10. Miscellaneous

Fundamental numerical studies of free convection in the spherical annulus and in a spherical sector reveal a number of interesting structural aspects of the flow and heat transfer, including hysteresis effects, branch solutions, and local heat transfer coefficients [98F, 99F].

The study of free convection loops placed in a magnetic field has been reported in connection with the development of MHD power generators [96F, 97F], and an analytical model has been developed for the induced electric current from such a loop [95F].

An experimental study of longitudinal temperature distributions in double-glazed window cavities has highlighted the role of convection in overall heat transfer process [93F]. With a focus on free convection in complex, partitioned flow geometries, Dyko and Vafai [94F] have reviewed all of the factors related to the optimal thermal design of aircraft braking systems.

9. Natural convection — external flows

9.1. Vertical plate

Studies on buoyancy driven convection heat transfer from a vertical plate include flows of power-law non-Newtonian fluids [6FF] and micropolar fluids [2FF] A new physical model [5FF] predicts the onset of transition along a vertical plate, while several turbulence models describe the turbulent flow along a flat plate within an isothermal cavity [1FF]. An analytical and experimental study of conjugate natural convection shows the interaction between a fluid and slabs of different material [7FF]. The influence of horizontal rectangular grooves on a vertical plate on the local and average heat transfer [8FF] as well as influence of the equivalent of venetian blinds on heat transfer from a vertical surface [9FF] have been studied. Numerical studies describe transient natural convection from surfaces with an oscillating mean surface heat flux [4FF] and a sudden change in surface temperature [3FF].

Other studies of flows on vertical plates include thermocapillary convection to bubbles in close proximity to a heated wall [12FF], and the flow and heat transfer with falling liquid films [11FF], including the influence of gas absorption [10FF].

9.2. Horizontal and inclined plates

A study of the transient cooling of a thin horizontal plate [13FF] in an isothermal cavity uses asymptotic and numerical techniques. Numerical solutions of the flow and heat transfer from a vertical rectangular fin attached to a partially heated horizontal base have been reported [14FF].

9.3. Cylinders and blunt bodies

An analysis [19FF] describes the heat transfer from horizontal cylinders at small Grashof number, while experiments [22FF] indicate the influence of humidity on convective heat transfer from small cylinders. Entropy generated in laminar natural convection from a horizontal isothermal cylinder has been described [15FF]. Analyses for unsteady flows include thermal and solutal buoyancy forces [20FF], combined heat and mass transfer [16FF] and convection in the stagnation point region of a three dimensional body [21FF]. Convective heat transfer from a complex surface has been described analytically [17FF], while heat transfer including interaction with pyrolosis on different shaped obstacles [18FF] and plumes from a vertical cylinder [23FF] has been studied experimentally.

9.4. Mixed convection

Mixed (combined forced and natural) convection studies consider the influence of a magnetic field on oscillating convection [28FF], boundary layer flow of a micropolar fluid on a horizontal plate [26FF] and flow over an isothermal plate of a variable viscosity [27FF] fluid. Similarity, solutions include diffusion and chemical reaction over a moving horizontal plate [25FF] and the influence of a continually stretching sheet on convection [24FF].

9.5. Miscellaneous

Analytical solutions describe the performance of pin-fin heat sinks [31FF], while experiments on the heat flow from helical coiled tubes in air [29FF] show the influence of various factors on overall heat transfer. The cooling capacity in electronic equipment casings [33FF] and convection in electro-chemical systems [32FF] have been described. Calculations show the heat transfer losses from various surfaces held inside a room that includes heated walls, floor and ceiling [30FF].

10. Rotating surfaces

10.1. Rotating disks

Two experimental studies considered the effect of a jet on a single rotating disk [2G, 3G]. Several theoretical studies were performed on heat and mass transfer to a spinning disk [1G, 5G, 7G, 8G]. The heat transfer within two parallel rotating disks was also investigated [4G, 6G].

10.2. Rotating channels

Cooling of gas turbine engine components continues to be a driving force in the study of flow and heat transfer in rotating channels. Several authors studied the flows in rotating rectangular channels, some with ribbed surfaces [12G, 17G, 20G, 24G]. Experimental and numerical investigations were performed on rotating two-pass channels of rectangular cross section [11G, 14G–16G, 23G, 25G]. The effects of jet impingement [9G, 27G, 28G] wall transpiration [19G] and ejection holes [26G] were reported for rotating rectangular channels. Flow and heat transfer were investigated in rotating smooth-walled tubes [21G, 29G]. The effect of a rotating inner cylinder on forced convection through a concentric cylindrical annulus was studied [18G, 22G, 30G]. Numerical solutions were presented for mixed convection in a horizontal cylindrical annulus when the inner cylinder [13G] or outer cylinder [31G] rotates. A numerical solution was obtained for the case of a gas-filled rotating annulus [10G] when strong natural convection is present.

10.3. Enclosures

A review of fluid motion inside rotating cylindrical containers was given [35G]. Heat and mass transfer within rotating horizontal convection layers was investigated [33G, 34G, 43G]. Experimental results were presented for unsteady thermal convection within a vertical circular cylinder and a section of a cone heated from below [36G, 37G]. The effects of a rotating oscillating endwall disk on a vertical circular cylinder was investigated [38G]. Numerical solutions were published for mixed convection in a spherical annulus rotating about its vertical axis [41G]. Applications of heat transfer in rotating enclosures include food-containers [42G], heat pipes [39G], condensers [40G] and rotary kilns [32G].

10.4. Cylinders, spheres, miscellaneous shapes

Mass transfer from a rotating cylinder with an impinging slot jet was measured [46G, 47G]. Other rotating geometries that were studied include spheres [48G], cubes [44G] and turbine blades [45G].

10.5. Miscellaneous

Heat transfer between two opposed counter-rotating jets was reported [50G]. An investigation into the performance of a centrifugal bubbling apparatus was presented for use in gas–liquid contact processes [49G].

11. Combined mass and heat transfer

11.1. Ablation and transpiration

A number of studies in the area of ablation were performed. Two of the investigations considered heat transfer and thermal stresses during the ablation of ceramics. The first utilized a numerical model to predict temporal temperature fields during laser drilling [3H]. The second focused on the experimental measurement of laser reflectance and surface temperature on a variety of composite materials [7H]. Another study developed a general departure function to characterize ablation of a cavity in comparison to ablation of a flat plate [4H]. Researchers also utilized experimental data in developing numerical models to describe the ablation of volatile films [1H]. In addition, a fully three-dimensional k–ε model for the laser heating of solid substances with gas impingement was developed [5H].

A computational study utilizing the vorticity–velocity method was performed to examine the effects of wall transpiration the convective flow, and heat transfer in the entrance region of horizontal ducts [2H]. Transpiration was also studied in a large scale, environmental context. Investigators used an extensive global root database to describe the root distribution in a widely-used land model [6H]

11.2. Film cooling

The effect of unsteady flow on film cooling was studied. Investigators considered the effect of an unsteady wake [13H], periodic unsteady wakes with varying free stream turbulence [16H] and bulk flow pulsations [21H]. The effect of coolant density, and blowing rate was studied [14H]. The effect of turbulence in single and staggered rows of cooling holes on the effectiveness and heat transfer was considered [8H–10H]. In addition the effect of the length-to-diameter ratio on the mean velocity and also on the turbulence intensity [12H] were studied. Water–air cooling technology was applied to the cooling of turbine blades [20H]. Numerical simulations were used to study heat transfer characteristics of compound angle holes [19H], the film cooling effectiveness of a flat plate by a row of laterally injected jets [18H], and evaporative cooling of liquid films in turbulent mixed convection channel flows [23H]. Heat and mass transfer in a heated vertical tube in the presence of a falling film of water on the inside wall was studied [17H]. The influence of flow leakage through a gap on the performance of film cooling [24H], and the film cooling effectiveness produced by slot injection into a uniform cross flow was studied [15H]. The results of experiments were used to assess the performance of algebraic models in predicting heat transfer with supersonic film cooling [11H]. A fuel film model incorporating both spray–wall and spray–film interactions was developed for use in the simulation of combustion [22H].

11.3. Jet impingement heat transfer — submerged and liquid jets

In studying the heat transfer due to submerged jet impingement, several numerical techniques were utilized. In the Reynolds-averaged context, investigations focused on the fluid flow and heat transfer characteristics on both single [33H], and multiple [43H] jets impinging on confined surfaces. Large eddy simulations were used to study the impingement of both round and planar [36H, 42H] jet impingement. Direct numerical simulation was used to investigate the impingement of a round jet into a parallel disk [39H]. An experimental study on the isothermal convective mass transfer behavior of a circular cylinder exposed to an air jet was performed [38H] The effect of the angle of inclination on the heat transfer characteristics was considered [40H, 32H]. Experiments were used to develop correlations for mass transfer efficiencies for a hot air jet impinging on a cool water surface [31H]. The impingement of liquid nitrogen jets on one another at supercritical pressure and temperature was studied [41H]. The flow structure of inclined jets [34H] and confined jets [27H] impinging on a flat plate was examined. Liquid jet and spray impingement cooling were studied [35H, 26H]. Forced and mixed convection heat transfer from an array of cylinders to a liquid jet was studied for a range of Reynolds, Prandtl, and Grashof numbers [25H]. Distributions of the local heat transfer coefficient were measured in a model engine wall [28H]. Researchers also considered the effects of jet swirl, oscillation, and spread in combined heat and mass transfer jet impingement [29H, 30H, 37H].

11.4. Drying

Heat and mass transfer are integral to drying. Several studies considered the drying of foodstuff. In the drying of fruits and vegetables, investigators performed both experimental studies [56H, 95H, 44H, 76H–78H, 84H, 86H] and numerical modeling and simulation [49H, 79H, 80H, 87H, 59H, 65H]. These include simulation of the cooling process for tortillas [97H], in which a model was developed to predict temperature, moisture content, and water activity of evaporatively cooled tortillas, and the simulation of deep bed drying of hazelnuts [69H]. Investigators also performed a combined experimental–numerical investigation of the heat and mass transfer in cheddar cheese during cooling [51H, 88H] and food products during bulk forced-air precooling. Recent investigations also include heat and mass transfer during refrigeration [48H], frying [53H, 72H, 68H] and microwaving [70H]. In addition to foodstuff drying, investigators considered the drying of non-foodstuff material [52H, 94H, 71H, 96H, 82H, 74H, 67H, 57H, 60H]. These include both theoretical

[83H], and experimental [100H, 85H] drying of paper, and the drying of polymer films [47H, 63H, 45H]. The drying of soils and crops was studied. These include the modeling of coupled heat and mass transfer in a solar crop dryer [54H], the development of heat and mass transfer relations [62H], and a fully three-dimensional, numerical simulation of heat and mass transfer in unsaturated soils [99H]. Researchers also investigated a variety of drying techniques [64H, 89H–92H, 46H, 50H]. Mathematical models were developed to predict moisture content and temperature in an indirect contact rotary dryer [93H]. Modeling and simulation was utilized in studying industrial convective dryers [73H] and spouted bed dryers [55H]. In addition, a simulation tool which models the dryer section of a paper machine was developed [58H]. Other studies include the investigation of spray dynamics in a pilot spray dryer [75H], the analogy between heat and mass transfer during the drying of liquid materials [81H] the modeling of forced-air precooling [61H], the modeling of hydrothermal and hydromechanical behavior of clay barriers [98H], and the measurement of tree transpiration in forests [66H].

11.5. Miscellaneous

A variety of studies in which heat and mass transfer occurs in combination have been performed. Several included the utilization of computational fluid dynamics (CFD) in studying heat and mass transfer [113H, 101H, 106H]. CFD was also used in the development and assessment of models in combined heat and mass transfer [114H]. Hydrodynamic effects were also considered; investigators studied the effects of density and pressure gradients [107H], coherent structures [104H], instabilities due to an unsteady density stratification [109H], intense mixing [110H], and natural convection [112H]. Researchers studied heat and mass transfer in the presence of non-isothermal chemical reactions [108H]. Researchers also considered the redistribution of soil water by tree roots [102H], the modeling of confined multi-material heat and mass transfer [103H], and the influence of local feedback mechanisms on land–air energy and mass exchange [111H]. In addition, transfer from internal flows to hemispheres and flat plates was made using the napthalene sublimation technique [105H].

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 five major categories: droplet and film evaporation (27 papers), bubble characteristics and boiling incipience (19 papers), pool boiling (43 papers), flow boiling (30), and two-phase thermohydraulics (13). In addition to these 132 papers, the interested reader will find reference to studies of evaporative and ebullient heat transfer among the papers included in: change of phase — condensation (JJ), heat transfer applications — heat pipes and heat exchangers (Q), and heat transfer applications — general (S).

12.1. Droplet and film evaporation

The 1998 archival literature provides several fundamental studies of droplet evaporation, including the introduction of a new dimensionless group [17J], the development of a numerical solution algorithm [7J], detailed numerical simulation of hollow-cone water sprays [9J], and evaluation of non-equilibrium effects in droplet-laden flows [13J]. The evaporation of solution droplets was examined in [4J] for binary fuel mixtures, in [10J] for ideal mixtures of alcohols, and in [26J] for spray pyrolisis in which solute precipitation effects must be addressed. The evaporation of a single droplet on a solid surface, using a molecular dynamics simulation method, is described in [11J], weak evaporation (or condensation) on a sphere in [20J], and direct contact evaporation for a droplet rising in an immiscible liquid in [23J].

The evaporation of atomised droplets in a turbulent environment attracted considerable attention in the two-phase community. [18J, 19J] used enhanced phase-Doppler anemometry to explore droplet collisions and coalescence, secondary atomization, and air stream heating. While the results of a direct numerical simulation of evaporating droplets in low Mach number flows was reported in [12J], [2J] provides numerical results for the effects of gas temperature fluctuations on a turbulent evaporating spray. The influences of inlet gas swirling and heating on droplet evaporation are described in [27J].

Growing interest in applications of evaporative cooling and optimization of evaporation processes prompted the development of a general mathematical model of evaporative cooling devices by [8J]. Evaporation of liquid films is described in [15J] dealing with the influence of wall proximity on the interface equilibrium temperature, in [14J] dealing with the evaporation rates at the tip of the liquid wedge under a bubble, and in [1J] providing a considerable extension of the database and correlations. [21J], [5J], and [3J] describe evaporation processes associated with solar stills, desalination process, and food preservation, respectively. [16J] explores evaporating flows in microchannels, [25J] presents system-level analyses of 'first-wall' liquid surfaces for high power fusion reactors, and the film evaporation of refrigerants, flowing in small diameter tubes, is the subject of [24J] and [22J].

Heat transfer correlations for evaporation in thermosyphons are presented in [6J].

12.2. Bubble characteristics and boiling incipience

The dynamics of vapor and gas bubbles in unconventional environments attracted considerable attention from the two-phase flow community. The behavior of preheated gas bubbles injected into a liquid bath is described in [32J]. [29J] proposes a microwedge model to explain binary mixture bubble growth and departure under microgravity conditions. [35J] presents the results of a comprehensive numerical simulation of a single vapor bubble of variable radius moving in a superheated or subcooled liquid. [46J] points to the benefits of a bubble sliding along the heated surface to explain the higher heat transfer coefficients observed for downflow than upflow flow boiling. [28J] reports on the use of a photographic technique to determine vapor volume flow departing from a single wire. While the effects of electric fields on the behavior of a bubble attached to a wall is the subject of [33J], the growth and collapse of a bubble in an ultrasound field is studied in [44J]. The effects of oil enrichment at the interface of a bubble embedded in an infinite refrigerant–oil mixture are described in [40J].

Bubble formation was the subject of several studies, including [37J, 36J] in which microscale homogeneous nucleation was observed, [31J] in which an interphase fluctuation propagation model is proposed to explain heterogeneous nucleation processes, [34J] which identifies a new liquid–vapor interface instability and its impact on bubble formation in microgravity, and [42J, 43J] which discuss the effect of microchannel spacing on bubble formation. Boiling incipience in supercritical fluids is reported for the first time in [45J]. Bubble formation and growth during underwater detonations are studied experimentally in [38J, 39J] and film boiling incipience directly from natural convection is described in [30J]. In [41J] vapor generation during flash boiling is described.

12.3. Pool boiling

Many of the pool boiling heat transfer studies in the 1998 literature deal with extension of the ebullient transport knowledgebase to unconventional fluids, environments, and geometries. [73J] describes the influence of subcooling on the pool boiling of methanol on a tungsten wire, while [57J] reports on the nucleate pool boiling of mercury in the presence of a magnetic field. [85J] deals with the simulation of film boiling near the thermodynamic critical point. The impact of long-term reduced gravity on pool boiling and bubble dynamics is reported in [80J], the use of an electrical body force to simulate the effects of variable gravitational acceleration on pool boiling in [84J], and the interaction of an acoustic field with boiling, at both terrestrial and microgravity conditions, is described in [82J, 83J]. A new theoretical model for the pool boiling of binary mixtures is offered in [65J], while experimental results for nonazeotropic binary mixtures of refrigerants are reported in [63J], for binary hydrocarbon mixtures in [48J], and water/propanol mixtures — over a range of gravitational accelerations — in [47J].

Nucleate pool boiling on downward and upward-facing, inclined surfaces is detailed in [77J], on a downward-facing hemispherical surface in [61J], along a heat exchanger tube in [55J], on the outside of a horizontal tube in [56J], and on the inside of relatively large diameter short tubes in [66J]. The studies documented in [58J, 49J] explore boiling in a narrow vertical slot, while [59J] presents an extensive compilation of data for boiling in a small cylindrical enclosure, [86J] provides data on ebullient cooling of a power module, and [87J] discusses parametric effects on boiling in a closed two-phase thermosyphon.

In boiling heat transfer, the Critical Heat Flux (CHF), or 'crisis,' represents the heat flux value at which vapor blankets the heater surface and the heat transfer coefficient deteriorates. [81J] describes a new dry-out mechanism for the pool boiling crisis and [78J] offers new observations on the liquid–solid contact patterns and bubble structure distribution at fluxes approaching the CHF value. Critical heat flux in concentric-tube open thermosyphons and vertical, closed-bottom rod bundles is discussed in [64J] and [69J], respectively. A CHF correlation for droplet impact cooling is the subject of [62J].

Despite the relatively high heat transfer coefficients associated with boiling heat transfer, considerable effort is devoted to the identification, development, and implementation of pool boiling enhancement techniques. In [75J] attention is focused on boiling from a uniform thickness pin fin, in [74J] on the enhancement associated with boiling on micro-graphite-fiber composite surfaces, in [89J] and [79J] on the use of surfactants to enhance nucleate boiling, in [68J] and [67J] on the use of electrical fields on pool nucleate boiling from heat exchanger tubes, and in [88J] on the influence of electric fields on film boiling. The bubble characteristics and governing phenomena responsible for the effectiveness of ebullient thermal transport from structured enhanced surfaces is described in a series of publications by Webb and Chein [50J–54J].

Film boiling heat transfer is the subject of several publications, including [76J] presenting a correlation for binary mixture, pool film boiling on horizontal cylinders, [71J] presenting an analytical solution for film boiling on spheres and vertical plates, [60J] offering a theoretical dry-spot model for transition boiling,

[72J] exploring the amplification of wall temperature fluctuations during transition pool boiling, and [70J] which describes the effect of refractory paints on mist flow heat transfer rates from metallic surfaces.

12.4. Flow boiling

The broad range of interactions between a pumped flow of liquid and vapor bubbles generated and released on a heated surface provide a large number of flow boiling heat transfer mechanisms and a diverse flow boiling literature. The primary research and modeling challenges facing the two-phase community are reviewed in [117J] and are reflected in the 1998 archival literature. A numerical simulation technique is described in [96J], a broad review of subcooled flow boiling correlations and flow regimes in [98J], a technique for identifying the thermal equilibrium entry length is presented in [91J], and experimental results for flow boiling in sub-atmospheric, vertical flow in [105J].

The influence of channel geometry on ebullient thermal transport is the subject of [106J] — where attention is focused on a heated inner annulus, of [109J] — dealing with a nonuniformly heated surface, and of [107J] and [112J] — addressing behavior in small-diameter tubes and microchannels, respectively. The efficacy of several flow boiling enhancement techniques is reported in [95J] — dealing with nitrogen flowing over a structured surface, in [104J] — dealing with the use of annular crevices, and in [114J] reporting the results of interference sleeves on cylinders. Field effects were addressed by [99J], which describes the effect of an electric field on flow boiling heat transfer and by [110J] which provides results of an experimental study of flow boiling under microgravity conditions.

The archival literature of 1998 provides insight into progress in the understanding and enhancement of the flow boiling 'crisis,' including both critical heat flux and dryout. A new dry-spot model for CHF prediction is the subject of [92J], the prediction of liquid film dryout in narrow channels is the subject of [116J], a method of calculating dryout and post-dryout heat transfer in tubes is described in [94J], and CHF on rod bundles in [103J]. The critical heat flux from a simulated microelectronic chip is discussed in [108J] and enhancement of CHF with microchanneled surfaces in [113J].

Flow boiling heat transfer of refrigerants attracted considerable attention, including a 3-paper sequence by Thome and co workers [100J–102J] on the relationship between two-phase flow patterns and heat transfer for refrigerants in horizontal tubes, [115J] on the heat transfer characteristics of microchannels, [90J] and [111J] on the thermofluid behavior of finned tubes, [118J] and [119J] on flow boiling of refrigerant/oil mixtures in microfin tubes and plain tubes, respectively, and [97J] and [93J] on flow boiling heat transfer to binary mixtures of refrigerants.

12.5. Two-phase thermohydraulics

The design of flow boiling systems must include attention to the thermohydraulic aspects of two phase flow. Contributions to the 1998 archival literature in this domain included: [127J] — which presents a coupled phasic exchange algorithm for the prediction of general two-phase flows, [120J] — which applies control analysis techniques to the determination of the boiling boundary in a heated channel, [124J] — which offers a new transition boiling model for use in the Relap5/mod3 computer code, [131J] — which explores two-phase instabilities in a natural circulation loop, [130J] — which offers data for flow in slightly inclined tubes, [132J] — which develops an analytic interfacial area equation, and [125J] and [121J] — which deal with determination of void fraction distributions using electrical impedance measurements and gamma densitometry, respectively.

The dispersion of two-phase releases is the subject of [122J] and [129J]. A numerical simulation of the nonhomogeneous flow in a diffuser pipe is presented in [123J]. Aspects of slug flow are explored in [126J] — focusing on the onset of slugging in a stratified flow approaching a junction and [128J] — the role of longitudinal dispersion in fully-developed slug flow in a channel.

13. Change of phase — condensation

Papers on condensation during 1998 were separated into those which dealt with surface geometry 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.

13.1. Surface geometry and material effects

One paper in this category dealt with the effect of surface conductivity [2JJ]. A hygrogenated carbon film for promoting dropwise condensation of steam was coated on various metallic surfaces. Three papers focused on the nature of the surface material. One discussed the hygrogenated carbon film [3JJ], another was on a PTFE coating [4JJ], and a third was with a composite nickel–PTFE plated coating [1JJ]. The last in this category dealt more with the coating processes, but did discuss a synthesized surface with a polymer film for enhanced heat transfer in steam condensers [5JJ].

13.2. Global geometry and thermal boundary condition effects

Several papers presented results for condensing flow within configured tubes. In the first, heat transfer coefficients for condensation of steam on thick-walled horizontal tubes were given [14JJ] and, in another, a review of techniques for integral, finned tubes was presented [7JJ]. A numerical analysis was documented for vertical, finned surfaces to show the effects of fin shape on heat transfer enhancement [13JJ]. Several papers addressed condensation inside tubes. In one, regimes were described for flow in smooth, horizontal tubes [9JJ]. Another discussed the value of microfinned surfaces in horizontal tubes [15JJ]. A correlation equation was given, including the effects on pressure gradient. In a third, flow maps and transition points were documented showing the effects of inclination angle for R-11 condensation in smooth tubes [17JJ]. And, in a fourth, the effects of coiled wire inserts in a horizontal tube were evaluated [6JJ]. The measurements indicated a doubling of the condensation heat transfer coefficient due to the coil. Several papers addressed nuclear reactor geometries. One addressed the loss of coolant accident in the cold leg of a primary loop [10JJ], another presented a model for condensation in a containment [11JJ], and a third discussed the effects of condensation on depressurization during a fusion reactor ingress-of-coolant event [16JJ]. One paper presented a numerical prediction of the performance of a high-efficiency boiler [12JJ] and another released a model for optimization of falling film evaporation in a desalination plant [8JJ].

13.3. Modeling and analysis techniques

An article was presented on the fundamentals of condensation heat transfer, including the complications which arise with forced convection [26JJ]. Another accounted for the effects of subcooling of condensate when there is a variable temperature surface [24JJ]. A stability analysis was presented for film-wise condensation where it was noted that the surface tension always stabilized a film but the effects of van der Waals force depend on the Hamaker constant [23JJ]. An analysis was presented for condensation with external flow over a horizontal tube [27JJ]. A single-tube model was presented for predicting the frequency characteristics of multi-tube, two-phase, condensing flow [21JJ]. A weakness of a previous equivalent Reynolds number model was noted and modifications were recommended for condensation in smooth tubes [25JJ]. In a similar paper, the utility of the equivalent Reynolds number model for application to condensation in small diameter tubes was shown [31JJ]. Two papers were with the reactor analysis program — RELAP. In one, a direct contact condensation model was developed, including the transition criteria [22JJ] and in another, a comparison of models in the program was made [18JJ].

One paper dealt with cooling tower analysis. It presented a study of non-equilibrium characteristics of mixtures and noted an unusual rise in interfacial temperature immediately below the onset of condensation [29JJ]. A model was presented for the growth of microdrops in inert gases when the droplets are of the size of the mean free path [19JJ]. A model was presented for the condensation coefficient of superheated vapor condensing inside of tubes [30JJ]. A numerical model for including the effects of the sorption curve was formulated for condensation on rotary heat exchangers [28JJ]. Rules for fitting the condensation curve with piecewise linearization were given [20JJ].

13.4. Free surface condensation

Two papers focused on free surface condensation. In one, a model was presented to predict drop size distributions in dropwise condensation [32JJ]. Thermal resistance in the drop and the promoter layer must be included in the analysis. Another experimented with choking and the behavior of under-expanded vapor jets [33JJ], where a model was developed which included entrainment and condensation effects.

13.5. Binary mixtures

Several papers were with multiple components. In one [34JJ], the effects of having noncondensables were addressed for vertical plates, to give the fin temperature and heat transfer coefficient distributions. Another addressed steam condensation augmentation with methylamine [38JJ]. A third presented a model which describes the effect of back diffusion for turbulent flow condensation in tubes with nonazeotropic binary refrigeration mixtures [37JJ], while a fourth, also with nonazeotropic refrigerant mixtures, discussed the effects of non-ideal properties [39JJ]. Marangoni convection was experimented upon under condensation in binary drops [36JJ]. A data set for model evaluation on multicomponent condensation in the shell and tube configuration was presented [40JJ]. The effect of noncondensables on condensation in a rotating drum, with scraper, was analyzed [41JJ]. Finally, condensation in premixed flame quenching was discussed [35JJ].

14. Change of phase — freezing and melting

14.1. Melting and freezing of sphere, cylinders and slabs

Freezing studies in cylindrical, ellipsoidal, slab, plate and miscellaneous geometries were presented in this section. In cylindrical geometry the studies included: a study of supercooling phenomenon and freezing probability of water inside horizontal cylinders [3JM]; an analytical study of natural convection on cryogenic pipe freezing [9JM]; freezing and melting with multiple phase fronts along the outside of a tube [14JM]; and frost deposition on a cylinder in cross flow [13JM]. In elliptical geometry an analytical solution of the heat transfer process during contact melting of PCM inside a horizontal elliptical tube was presented [4JM], as well as heating and melting of slender samples in monoellipsoidal mirror furnaces [7JM]. Slab geometry studies included: interface temperature during high-Peclet number flow over a flat substrate [2JM]; measurement of the heat transfer coefficient in food thawing using an infinite slab geometry approximation [6JM]; and undercooling and contact resistance in stagnation-flow solidification on a semi-infinite substrate [12JM]. A study in plate geometry of solidification of pure metals using Greens functions was presented [8JM].

Several other miscellaneous geometric studies were presented including melting and solidification in multi-dimensions with more than one interface [5JM], 1D phase field models with adaptive grids [10JM], a moving boundary problem in a finite domain [11JM], and evolution of ice over freezing winter leads in Arctic waters [1JM].

14.2. Stefan problems

Studies included: a novel enthalpy formulation applied to Stefan problems in various domains [15JM]; and imposition of an energy balance condition on a phase change interface with thermal wave effect [16JM].

14.3. Ice formation in porous materials

Work in this area included freezing in traditional porous material freezing as well as in foods and biologically relevant material (cryobiology). Studies on traditional materials included: heat and mass transfer in freezing and frozen peaty soils [23JM]; seasonal fluxes of water and heat in the active layer from spring thaw to fall freeze-back in a permafrost site [20JM]; density effect on laminar water pipe flow solidification [28JM]; eutectic freeze crystallization used in waste water purification [29JM]; and glass transition and relaxation kinetics of polymers studied with DSC techniques [24JM].

In food science investigations included: food freezing and chilling behavior using an enthalpy based technique [17JM]; a review of thermal design calculations for food freezing equipment [21JM]; experimental and theoretical study of model food freezing [30JM]; and simulation of ice recrystallization in ice cream during storage [18JM]

Investigations in the cryobiology area included: influence of anti-freeze proteins on the freezing of cell suspensions [25JM]; freeze–thaw of bovine embryos in the presence of propylene glycol and ethylene glycol protective additives [22JM]; optimization of high pressure freezing for a new microbiopsy device [26JM]; assessment of the properties of pure water and solute laden solutions at low temperatures and in the solid phase [27JM]; in situ assessment of cell viability after freezing [31JM]; and thermal analysis of a cryomicroscope due to heat spreading and contact resistance [19JM].

14.4. Contact melting

Studies included: effects of vibration on ice contact melting within rectangular enclosures [32JM]; effects of transverse convection and s/l density difference on the steady close-contact melting [33JM].

14.5. Melting and melt flows

Experimental work in this area included: interactive solutal and thermal Marangoni convection in a metal melt during directional solidification [34JM]; visualization of melting and solidification in convecting hypoeutectic gallium alloy [35JM]; heat transfer, fluid flow and interface shapes in zone melt processing with induction heating [39JM]; thermocapillary convection in two-layer systems [41JM]; factors affecting solder microdroplet deposition [48JM]; interface propagation in the processing of metal matrix composites [36JM]; and continuous fractional crystallization on a moving cooled belt [42JM].

Numerical studies in this area included: use of a modified control volume model to predict natural convection dominated melting of pure metal [38JM]; a model of marangoni effects in electron beam melting [40JM]; modeling of micro-level volume expansion during reactive melt infiltration [43JM]; a moving grid approach to modeling melt in phase change problems [44JM]; simulation of the melting of a horizontal substrate placed beneath a heavier liquid [45JM]; modeling of convective heat transfer in horizontal zone melting [46JM]; a model of 3D laser heating including moving heat source and phase change [49JM]; heat and solute diffusion with a moving interface by BEM [50JM]; and FEM analysis of heat and fluid flow in an electron-beam vaporization system for metals [47JM].

In addition a hypothesis concerning the evolution of the earth's mantle was proposed as caused by a planetary collision. The impact is suggested to have formed a melt ocean of magma which floated the mantle [37JM].

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

Experimental work in this area included: nickel aluminide intermetallices synthesis using a spray atomization and deposition technique [55JM]; observation of inclusion behavior in a steel melt by the advancing melt/solid interface [57JM]; differential thermal analysis DTA) study to determine thermal property changes of mold powders used in continuous casting of steel slabs [58JM]; thermal process in high velocity oxygen-fuel (HVOF) spray coating on a copper substrate [59JM]; melting and resolidification of subcooled mixed powder bed with moving heat source [60JM] and heat transfer through source powder in sublimation growth of SiC crystals [53JM].

Modeling work in this area included: modeling of the melting of solid particles in an agitated molten metal bath [51JM]; 3D simulation of dendritic grain structures of gas-atomized Al–Cu alloy droplets [52JM]; modeling of particle behavior of nanocrystalline Ni during high velocity oxy-fuel thermal spray [54JM]; and free surface shape and temperature distribution in liquid metal droplets produced in the TEMPUS electromagnetic levitation facility [56JM];

14.7. Crucible melts

A crucible melt numerical study of combustion in a zinc flash smelter was reported [61JM].

14.8. Glass melting and formation

Reports include: an FEM study of bouyant flow of an optically thick fluid representative of molten glass [62JM] and evaluation of bubble removing performance in a glass furnace [63JM].

14.9. Welding

Welding work included: modeling of resistance welding of thermoplastic matrix composite lap shear specimens [64JM, 65JM]; exothermically assisted shielded metal arc welding [66JM]; globular transfer in gas metal arc welding [69JM]; hot plate welding of polypropylene [72JM]; analysis of a weakly ionized plasma arc between geometrically dissimilar electrodes [73JM]; thermal modeling of laser welding for titanium dental restorations [74JM]; numerical dynamic analysis of a moving GTA weld pool [68JM]; modeling of GMA weld pools with consideration of droplet impact [67JM]; analysis of pulsed current GTA weld pool heat and flow fields [70JM]; and an FEM analysis of dual-beam laser welded tailored blanks [71JM].

14.10. Enclosures

Numerical work included: FVM and FEM simulation of macrosegregation of an alloy in a rectangular cavity [75JM]; natural-convection-dominated melting inside heated rectangular cavities [76JM]; FEM model for convection-dominated melting and solidification in a rectangular cavity [77JM]; and a FEM model of melting of a pure PCM in a rectangular container heated from below [78JM].

Other studies included: gas flow analysis in melting furnaces [80JM]; bifurcation and stability analyses for a two-phase Rayleigh–Benard problem in a cavity [81JM]; and an experimental study of melting heat transfer in an enclosure with three discrete protruding heat sources [79JM].

14.11. Nuclear reactors

A simulation of a fuel/coolant accident simulated by experiments on hot melt injected into sodium was presented [82JM].

14.12. Energy storage

Modeling work included: simulation of a multi-layer latent heat thermal energy storage system [83JM]; analysis of a latent heat thermal energy storage system with enhanced heat conduction using fins [84JM]; cyclic melting and freezing of an encapsulated PCM integrated into a solar heat receiver [85JM]; exergy analysis of latent heat storage systems with PCMs [91JM]; convection based modeling of vertical cylindrical storage unit for PCMs [87JM]; a numerical analysis of the stratification properties of chilled water storage tanks at the freezing point [93JM]; and a numerical study of vibration on melting of an unfixed rectangular PCM under variable gravity environment [92JM].

Other studies included: latent cold heat energy storage by oil droplets [86JM]; natural convection melting from a heated wall with vertically oriented fins [88JM]; improvements of heat transfer in latent heat thermal energy storage with embedded heat sources [89JM]; thermal management of an avionics module using s/l phase change materials [90JM]; and an experimental and analytical phase change study in an energy storage system [94JM].

14.13. Solidification during casting

Modeling of dendritic structure of steel billets processed by continuous casting was presented [95JM].

14.14. Mushy zone — dendritic growth

Modeling studies included: a numerical study of convection–diffusion phase change problems in the mushy region [96JM]; a continuum model of mass, heat and momentum transport in multicomponent s/l phase change [97JM]; modeling of dendritic tip temperature under conditions of free growth (no gravity) [98JM]; simulation of dendritic growth in a shear flow [102JM]; refined solute diffusion model for columnar dendritic alloy solidification [103JM]; thermal model for mushy zone formation in binary solutions [104JM]; and integral solutions of diffusion controlled dendrite tip growth [101JM].

Additional studies investigated the concave casting surface during mushy-zone solidification [99JM] and scaling behavior of 3D dendrites [100JM].

14.15. Metal solidification

Modeling studies included: computational study of planar solid–liquid interface stability during rapid solidification of binary metal alloys under laser treatment [105JM]; FEM and experimental analysis of compression holding in semi-solid forging [107JM]; numerical simulation of layer solidification for unsteady conditions in a eutectic binary fluid [109JM]; numerical analysis of pulsed laser heating for the deformation of metals [112JM]; numerical analysis of semi-solid forming technology for light metals in die casting; explicit interface tracking in three dimensions on a fixed grid during solidification [114JM]; numerical modeling of ductile iron solidification [115JM]; heat and mass transfer in solidifying binary alloy [116JM]; quantification of quenching thermal stresses and heat transfer [118JM]; evaluation of solutal, thermal and flow fields in unidirectional alloy solidification [122JM]; modeling the heat flow to an operating sirosmelt lance [123JM]; a mathematical model for free surface problems with application to solidification [125JM]; the influence of thermoelectric and magnetohydrodynamic effects on solidification [126JM]; the computer modeling of microstructural evolution and final properties of C-MN-NB steels [108JM].

Experimental studies included: melting and solidification characteristics of solders using DSC [106JM]; interfacial instability and microstructural growth during rapid solidification in laser processing [111JM]; squeeze casting and hot/cold forging [113JM]; layer merging during solidification of the supereutectic NH_4Cl–H_2O system [117JM]; rapidly solidified ^{12}Cr–Mo–V stainless steel [120JM]; melting and resolidification of a substrate in contact with a molten metal [124JM]; gamma titanium aluminide alloy phase change during supertransus heating [121JM]; stud-to-plate laser braze studied [119JM]; and the influence of quenched-in clustering of vacancies in electron–phonon coupling [110JM]

14.16. Crystal growth from melt

Experimental studies included: comparative study of crystallization and orientation development in melt spinning for polyolefin fibers [130JM]; columnar growth of melt-spun steel [135JM]; distribution of Sb dopant in Ge single crystals grown by the floating zone technique in space [138JM]; direct contact heat transfer in melt crystallization [139JM]; crystal formation in amorphous metals after heavy ion bombardment [156JM]; fragmentation of dendritic crystals during solidification of aqueous ammonium chloride [146JM]; cooling and crystallization of hot melt adhesives [131JM]; composition of MOVPE horizontal reactor grown ternary alloys [155JM]; gallium arsenide growth in a pancake and MOCVD reactor [148JM]; convective effects during liquid encapsulated crystal growth in a magnetic field [145JM]; effect of magnetic fields on heat flow and interfaces in floating zone silicon crystal growth [140JM]; floating zone growth of large silicon crystals with radiation on diffuse and specular surfaces [132JM]; radiation in silicon floating zone crystal growth furnace with specular reflection on concave surfaces [133JM]; thermo-flow structure during chemical vapor deposition epitaxy [153JM]; and creation of vicinal facets on the surface of epitaxially grown gallium arsenide [127JM]. In addition, a geological study of crystallization of the Skaergaard Layered Series geography was presented [152JM].

Modeling studies included: dopant segregation in vertical zone-melting crystal growth [142JM]; theoretical analysis of the micro-pulling-down process for fiber crystal growth [143JM]; dynamic simulation of vertical zone-melting crystal growth [144JM]; a model of thin-filament melt spinning [136JM]; transient growth analysis of LE–VGF growth of compound semiconductors [147JM]; and a computational study of smear-induced crystallization in polymers [149JM].

Additional work on Bridgman and Czochralski crystal growth was also presented. Bridgman growth studies included: temperature distribution and solid–liquid interface shape in vertical Bridgman crystal growth of semi-transparent materials [128JM]; bifurcation and stability analyses of horizontal Bridgman crystal growth of a low *Pr* material [141JM]; experimental determination and numerical modeling of s/l interface shapes for vertical Bridgman grown antinomide crystals [129JM]; local and global simulations of Bridgman and liquid-encapsulated CZ crystal growth [158JM]; and a review of heat and mass transfer during crystal growth — either CZ or Bridgman [137JM].

Studies on Czochralski crystal growth included: single CZ crystal growth of silicon with respect to specular and diffuse surfaces [134JM]; morphology and heat transfer in sillenite compounds grown by CZ method [150JM]; interface approximations in multi-domain simulations of CZ bulk flows [151JM]; flow and temperature in molten silicon during CZ crystal growth in cusp magnetic field [154JM]; and diameter controlled CZ growth of silicon crystals [157JM].

14.17. Casting

Experimental work included: radiative heat transfer through mold flux film during initial solidification in continuous casting of steel [163JM]; measurement of thermal resistance at the interface between mold flux film and mold [164JM]; heat transfer across mold flux film during initial solidification in continuous casting of steel [165JM]; experimental studies of heat transfer and solidification pertinent to strip casting [176JM]; roll strip interfacial heat fluxes and effect on microstructure in twin-roll casting of steels [178JM]; effects around the immersion nozzle in billet continuous casting mold [183JM]; and thermal stress during vacuum arc remelting and mold casting of ingots [160JM]. In addition, double-gated, modulated-pressure injection molding was reported by [184JM].

Modeling studies included: shape deposition manufacturing with microcasting using metal droplet deposition [161JM]; numerical step type technique for determining interfacial condition in die-casting [159JM]; a FEM formulation for solving transient multidimensional phase-change problems [162JM]; mathematical and physical modeling of steel flow and solidification in twin-roll/horizontal belt thin-strip casting machines [166JM]; simulation of microporosity formation in modified and unmodified A356 alloy castings [167JM]; modeling of transient flow phenomena in continuous casting of steel [168JM]; numerical modeling of heat transfer and fluid flow during casting [169JM]; numerical investigation of macrosegregation during thin strip casting of steel [170JM]; modeling of heat transfer between an iron casting and a metallic mold [171JM]; and a 3D model of continuous beam blank casting [172JM]; interfacial heat transfer during solidification and its use in design of optimal feeding of castings [173JM]; prediction of interfacial contact conductance of investment cast alloy [174JM]; 3D numerical prediction of turbulent flow, heat transfer and solidification in a continuous slab caster for steel [175JM]; computational fluid dynamics applied to twin-roll casting [177JM]; characterization of the mold metal interface effects in metal casting [179JM]; analysis of mold wear during continuous casting [180JM]; a mathematical study of EMBR ruler on the continuous casting process [181JM]; and external mold surface heat transfer applied to metal-matrix composite casting [182JM].

14.18. Splat cooling

Studies included: deformation and solidification of a droplet impinging on a flat surface [185JM]; and impact and solidification of till droplets on a steel plate [186JM].

15. Radiative heat transfer

The papers below are divided into subcategories, which focus on the different impacts of radiation. Papers describing the development or application of models dominate the literature on radiative heat transfer. Papers focusing on the new 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. However, compared to previous years fewer publications addressed this topic. Bazin et al. [3K] use a view-factor method to study heat transfer through X-rays in heavy-ion fusion. A semianalytical algorithm for calculating diffuse plane view factors is presented in [16K]. Nunes and Naraghi [21K] use a discrete exchange factor method to analyze transfer in axisymmetric enclosures. Monte Carlo methods are also used for tracking radiative paths [26K, 27K]. Jung et al. [12K] determine view factors for a crystal growth furnace.

This year, the discrete ordinate method is frequently employed to model radiative heat transfer in three-dimensional geometries. Nonorthogonal grids for complex 3D-geometries are used in [23K–25K]. Rectangular enclosures are modeled in [22K, 15K]. Jessee et al. [10K] use a discrete ordinate scheme with an adaptive grid refinement algorithm to solve the radiative transport equation. Irregular 3D-systems are modeled in [14K]. A discussion of the discrete ordinate method for participating media is given in [30K].

A comparison of discrete transfer, discrete ordinate and finite volume methods for 2D-systems is presented by Coelho et al.[6K]. The discrete ordinate and the finite volume method turn out to be the most economical ones. A finite volume method for three- dimensional enclosures is used in [1K]. Another method used to describe radiative transfer in complex geometries is based on variational principles [9K]. Cumber and Beeri [7K] discuss a strategy for parallelization of discrete transfer models. The finite volume method is used for axisymmetric enclosures [13K, 20K], and in complex geometries using unstructured meshes [19K]. Miller uses a Monte Carlo method for a random medium with plane geometry [17K]. The same author also describes a stochastic construction method for Feynman path integral representation of Greens functions [18K]. A second order finite difference scheme is used to model multidimensional radiation problems in the diffusion limit [8K]. Stasiek [28K] uses a transfer configuration factor method to model radiative transfer in open enclosures. A wavelet basic function method is used for the modeling of a one-dimensional equilibrium problem [2K].

The geometry of the system also plays an important role in the radiative heat transfer in catalytic monoliths [4K], in ultra-high temperature heat exchangers [11K], and in one-dimensional gas enclosures with reflective surfaces [5K]. The effect of the location of heating tubes in greenhouses is studied in [29K].

15.2. Participating media

Papers in this category can be divided into those, which focus on emission and absorption properties of the media, and those, which emphasize scattering.

This year, fewer papers consider radiative transfer in molecular gases. A macrostatistical model to describe the vibrational band spectrum of CO_2 and H_2O is used by Surzhikov [59K, 60K]. Isothermal water and $CO_2/H_2O/N_2$ mixtures are considered in a three-dimensional radiation analysis in [52K]. Liu et al. [51K] also present a new gray-band approximation which utilizes a local absorption coefficient. Gokcen et al. [43K] present simulations of emission spectra from shock-layer flows in an arcjet facility. Higano et al. [45K] discuss the heat transfer in large toroidal fusion plasmas by approximating the plasma as a gray, participating medium.

A good number of papers focus on the influence of scattering, absorption, emission, and reflection. Scattering and reflection are important in coating layers containing pigments [32K], since high reflectivities in the infrared can influence the combustibility of materials. Absorption is important for radiative heat transfer in suspensions [35K], in translucent thermal barrier coatings [55K], and in semitransparent molten glass jets [56K]. Vitkin and Ivanov [63K] discuss the heat transfer in a light-scattering and absorbing slab. The effects of scattering are emphasized in [54K, 61K]. Emission, absorption and scattering are considered for multidimensional geometries [53K], for media bounded by gray, diffusely reflecting and emitting enclosures [58K], for media between plane and concentric, spherical boundaries [64K], and for fluoride salt phase change media bounded by concentric cylinders [65K]. The unsteady cooling of solid spheres in radiatively active media is discussed in [34K].

Absorption and scattering are also pivotal for the radiative transfer in fibrous media as pointed out in [48K, 39K]. The radiative properties of fiber-reinforced aerogels are studied by Cunnington et al. [38K]. The influence of using Planck mean properties compared to spectral and flux-weighted properties when modeling radiative transfer in fibrous media is discussed in [31K]. The properties of participating media in combustion, flames and fires have attracted particular interest. Carvalho and Farias model heat transfer in radiating and combusting systems focusing on the radiative properties of combustion products [33K]. The radiative properties of the combustion products are important in heavy fuel oil combustion [62K], compartment fires [42K], and in radiative transfer in ceramic-coated furnaces [47K]. The radiative properties of the fuel are emphasized in the study of radiation reabsorption in CH_4/CO_2/air and $CH_4/CO_2/O_2$ premixed flames [44K], and of gas fired furnaces [50K]. Soot also has a strong influence on the radiative transfer in combustion and fires [46K, 40K, 41K, 36K, 57K]. Cumber et al. [37K] use a wide band radiation model for non-homogeneous combustion systems. Liakos et al. [49K] study radiative transfer in pulverized coal char combustion.

15.3. Radiation combined with convection, conduction or mass transfer

Within the papers on combined heat transfer modes most papers focus on two modes. A large number of publications address radiative heat transfer combined with convection.

Viskanta [98K] gives an overview of convection and radiation in high temperature gas flows. Radiation and natural convection are important for the heating element configuration of tunnel ovens [77K]. The combination of natural convection and radiative heat transfer also plays an important role for the scaling of organic light-emitting flat-panel displays [97K], and for large-eddy simulations of contrails [74K]. Numerical models for natural convection–radiation heat transfer are presented for arbitrarily shaped enclosures [94K], partitioned cavities [92K], the flow of optically dense fluids along cylinders with elliptic cross section [82K], and large vertical channels with asymmetric heating [73K]. Bril et al. [71K] present similarity laws for heat radiation from turbulent buoyant jets. The combined heat transfer upon turbulent flow of a high-temperature radiating gas past a thin semitransparent plate is studied in [95K]. Breitholtz and Leckner study the heat balance of a circulating fluidized bed furnace [70K].

Radiative transfer and forced convection for air in channels with offset plates is studied by Ali et al. [66K]. A computational model for heat transfer in very high temperature gas cooled reactors is presented in [68K]. Lee and Viskanta [88K] study the quenching of flat glass by impinging air jets. An infrared reflow oven with convection fan is considered in [84K].

Forced convection–radiation heat transfer is also considered important for turbulent flows of participating gases through ducts [79K], nonhomogeneous rectangular pipes [80K], and in chemical vapor deposition reactors [76K]. Fewer publications deal with the combined effects of radiation and conduction. Several papers deal with new approaches to the modeling of combined radiation and conduction. Andre and Degiovanni [67K] model a semitransparent layer by a matrix transfer function to solve the one-dimensional transient energy transfer by conduction and radiation. The integro-differential equation modeling in conducting, radiating and semi-transparent materials is described in [87K]. Banoczi and Kelley use a multilevel algorithm to solve the nonlinear system of equations for radiation–conduction transfer [69K]. Conduction–radiation in cylindrical media is studied in [86K], and in general axisymmetric media in [99K]. Conductive and radiative heat transfer are also important in glass manufacturing [89K, 96K, 85K]. Chen and Lin [72K] study heat and mass transfer in polymer solutions exposed to intermittent infrared heating and airflow.

Several papers consider combined convection, conduction, and radiation. Hossain and Rees [83K] study heat transfer from a vertical cylinder. Combined conduction–convection–radiation also plays a role in the heat transfer from residential attics [91K], heat transfer between insulated cables suspended in air [90K], for the flame shape and quenching in ducts [81K], for the modeling of lighting/HVAC interaction in enclosures [75K], and for the heating of continuously moving loads in industrial radiant ovens [78K]. A spray-cooling problem for hot surfaces is considered in [93K].

15.4. Intensely irradiated materials

Only few papers this year deal with intensely irradiated materials. Astafieva and Phrishivalko study the heating of solid aerosol particles exposed to intense optical radiation [100K]. Laser-driven shock waves are analyzed by Steiner et al. [101K] including radiative and conductive heat transfer.

15.5. Experimental methods and properties

Several papers are dedicated to the development of new experimental methods. High-Tc superconductors are considered for the design of far-infrared radiation modulators [109K], and for radiation detectors [110K, 106K]. A laser-flash method is used to measure the thermal diffusivity of semitransparent materials [107K]. The effect of Stefan flow on the characteristics of stable (burning) and critical (ignition and extinction) regimes of heat and mass transfer between a carbon particle and air is established in [105K]. Blackbody radiation of single spherical particles has been used to derive the surface temperature [104K]. Blackwell et al. [103K] report measurements of shock-layer vibrational populations and temperatures in nitrogen arcjets. A high-power, radiatively cooled hydrogen arcjet thruster is studied in [102K]. Shen et al. [108K] report measurements of absolute infrared intensities in thermal wave resonant cavities.

16. Numerical methods

The development and application of numerical methods continues to be an area of intense research activity. Newer procedures are developed for solving the partial differential equations involving heat conduction and fluid flow. Also, numerical methods are applied to a variety of practical problems. In this review, the papers that focus on the application of numerical methods to specific physical situations are included in the appropriate application category. The papers that describe the details of a numerical method are referenced in this section.

16.1. Heat conduction (direct problems)

A network model has been developed for heat conduction with varying thermal properties [6N]. A mesh-free method based on the method of fundamental solutions is described in [2N]. For the problem of obtaining iterative solutions of strongly nonlinear equations, an auto-adjustable damping method is proposed [1N]. Radial basis functions are used to create a mesh-free method for heat conduction [15N]. A finite-volume method is described for moving-boundary problems [16N]. The non-Fourier heat conduction problem is addressed in [13N, 9N]. A harmonic-sine procedure is described for heat conduction problems with singularities [11N]. A variational approach is presented for nonlinear heat conduction problems with random parameters [7N]. Reference [10N] shows the incorporation of anisotropic conduction using unstructured meshes. Nonlinear heat conduction in a system of different materials is treated [3N]. The diffuse approximation method is compared with a control volume method [12N]. Boundary element methods for heat conduction have been presented in [14N, 8N, 4N, 5N].

16.2. Heat conduction (inverse problems)

Inverse problems for the piezoelectric phenomenon have been considered in [20N, 21N]. Parabolic and hyperbolic inverse heat conduction are treated in [17N–19N]. An inverse geometry heat conduction problem is addressed in [23N, 24N]. The method of mode reduction is used for solving inverse heat conduction problems [25N]. A boundary element method is used for solving an inverse problem [22N].

16.3. Phase change

A numerical scheme is described for the Stefan problem [26N]. A moving-boundary technique is used for solid–liquid phase change [27N]. The dynamic behaviour of a melting sample is analyzed in [29N]. The solidification of binary alloys is addressed via an inverse domain problem [28N].

16.4. Treatment of convection and diffusion

A higher-order convection–diffusion scheme for thermally driven flows is described [31N]. A multifield model for advection-diffusion is presented in [34N]. Adaptive very-high-resolution schemes are proposed [32N, 33N]. Multilevel solution-adaptive strategies are examined on selected test problems [30N]. Preconditioning techniques for convection–diffusion problems are investigated [35N].

16.5. Solution of flow equations

A number of variations of the SIMPLE algorithm have been proposed and examined. A comparison of SIMPLE and PISO algorithms is described [36N]. Various pressure-based procedures are tested for the shock-tube problem [38N]. Convergence criteria for SIMPLE-based algorithms are examined [40N]. A pressure-based procedure is applied to duct flows [55N]. A multigrid algorithm is used in combination with the SIMPLE procedure [56N]. Reference [52N] describes the treatment of pressure boundary conditions for the flow equations. A SIMPLE-like algorithm on colocated grids is described in [54N]. A variant of SIMPLE for treating buoyancy-driven flows is presented [50N, 51N].

A finite analytic method is reviewed [44N] and applied to the flow equations [37N]. An adaptive finite element method is used for turbulent forced convection [39N]. A finite-element multigrid method is described for flow problems [41N, 42N]. Reference [49N] proposes techniques for exploiting the flexibility of unstructured grids. Artificial compressibility is used for computing flows with free surfaces [48N]. A diagonal Cartesian method is proposed for incompressible flows [43N]. A spectral domain decomposition technique is described for flow equations [45N].

A strongly coupled technique is used for non-Newtonian flow [53N]. A technique is proposed for the treatment of the singularity at the radial center in cylindrical coordinates [47N]. Benchmark solutions are presented for unsteady flow problems [46N].

17. Properties

In contrast with the investigations of the several preceding years interest has shifted to the characteristics of modern materials and their applications: composite systems, thin films and contact resistance.

17.1. Diffusion

Species transport by diffusion is measured in a liquid (5 mol% Sr-substituted $LaPO_4$) in the course of investigating the electrical conductivity. Critical constants of mass diffusion through a membrane are found to be related to a critical diffusion time marking the conversion between transient and steady-state conditions of the process [1P, 7P]. Analytical efforts determine the role of species diffusion in a multi component, reacting, laminar flow system involving heat and mass transfer; model the mass-transfer — controlled spherical bubble growth in a quiescent liquid, the dissolution of alumina in cryolite at elevated temperatures, and the behavior of an isolated fluid drop of a single compound immersed in another compound in finite, quiescent surroundings at supercritical conditions. The phenomenological diffusion equation for solute atoms under a temperature gradient is examined and a new error-estimating parameter in diffusion modeling proposed for certain engineering problems [2P–6P, 8P].

17.2. Thermal conductivity

Experimental measurements provide the effective thermal conductivity for beds of $CaCl_2$ reactive particles in the course of gas–solid reactions. For the magnesium–magnesium-hydride–hydrogen ($Mg–MgH_2–H_2$) packed bed system a new technique measures the effective thermal conductivity. Because Fe–Cr alloys with more than 30% (mass) chromium are potentially useful in many industrial applications, Mechanical and Physical properties were investigated for alloy systems in which Fe mass percent ranges from 50 to 70% (mass). Other works determine the thermal diffusivity of levitated, oblate, spheroidal samples by the flash method, model the thermal diffusion in a temperature — modulated differential scanning calorimeter and investigate the combined conductive and non-gray radiative heat transfer of open cell polyurethane (PU) foam [15P, 16P, 9P, 18P, 10P, 20P]. Using existing data the dependency of physical properties on temperature and composition for 11 alloys of the Al–M6 system are generalized to represent the full range of system behavior. Other solid phase systems are studied for calculating heat flow under inhomogeneous conditions and simply modeled for determining thermal properties and heat transfer coefficients when being refrigerated in any medium. A semitheoretical method is proposed for predicting liquid thermal conductivity and numerical methods for estimating temperature-dependent thermal conductivity and heat capacity using internal temperature measurements [19P, 14P, 13P, 17P, 11P, 12P].

17.3. Heat capacity

Calorimetric experiments yield data for *n*-C-8-, C-9-, and C-10-dimethylphosphine oxides, putidaredoxin (Pdx), an iron–sulphur protein containing a 2Fe–2S cluster, and a procedure for separating the enthalpic effect and the heat capacity. Additional works report values for lithium bis(trifluoromethylsulfone)imide (litfsi) (a promising electrolyte for high-energy lithium batteries), partial molar heat capacities for five linear alcohols and five N-substituted amides, and liquid ammonia [21P–23P, 26P–28P]. Analysis yields information about liquid selenium and a theoretical one-dimensional liquid of the Hubbard type [24P, 25P].

17.4. Composite materials

The behavior of the alloy, 2124 Al, reinforced by 20 percent (volume) silicon carbide particulates, is observed for creep at various temperatures and applied stresses. Using a thermal pulse technique, thermal diffusion through aluminum oxide/molybdenum multilayers is studied. Analytical works consider: two-dimensional, transient heat transfer in a multilayered system, composite materials with parallelepiped inclusions, and model rubberized materials undergoing thermal treatment [29P–33P].

17.5. Contact resistance

Adhesion and homogeneity of thin films are related closely to the subsurface physical and chemical properties. Interface thermal resistance and subsurface effusivity of submicron metallic films on substrates are determined simultaneously by experiment. Analytical investigations include: An analysis of the thermal resistance between two semi-infinite solids in contact due to the interstitial medium presence; the application of statistical mechanics to study thermal contact conductance; the success of existing analytical models in predicting the thermal contact conductance for aluminum/aluminum and aluminum/stainless-steel surfaces in contact; the efficacy of a modified thermal conductivity relation when modeling heat transfer through micron-sized caps in areas such as insulation and contact regions [34P–38P].

17.6. Thin films/coatings

There is considerable activity in this sector. Thermal waves are used to study the thermal properties of hard coatings and the heat transfer between the coating and piece. Joule heating of poly-silicon microstructures has scant influence on the Young's modulus of the microstructure. It is also used to determine the thermal conductivity of the passive, low dielectric-constant layers employed in integrated circuits (e.g. polymers and porous oxides) without knowledge of the layer heat capacity. Other papers describe the use of laser-flash method to measure the normal diffusivity of films (e.g., diamond) with thicknesses in the range 200–700 μm, a technique for measuring the lateral thermal conduction in a silicon layer, and the effects induced by electrical current (DC) on the adherence of thin gold films to the substrate [44P, 49P, 47P, 39P–41P].

Analytical efforts focus on: the three-dimensional modeling of heat flow into substrate with temperature dependent thermal conductivity; the effective thermal conductivity of a thin, randomly oriented, composite material; the prediction of thermal boundary resistance in thin-film, high thermal conductivity, superconductors; and the minimum thermal conductivity of thin-film materials [48P, 45P, 46P, 42P, 43P].

17.7. Transport properties

The flash method measures heat capacity, thermal conductivity, and thermal diffusivity for polycrystalline $ZnIn_2Se_4$ 300–600 K. Simple formulas (based on the latest, tabulated, experimental data) for liquid water (0–150°C) allow the full range of thermodynamic and transport properties to be calculated. Analytical studies: describe the use of genetic algorithms to design experiments and develop estimates for thermal properties; study the transport properties of multicomponent, reacting, gas mixtures using kinetic theory; determine transport coefficients and equation of state of supercritical fluids and calculate transport cross-sections and collision integrals for interactions of hydrogen atoms and diatomic molecules [50P–56P].

17.8. Viscosity

Measurement of the viscosity of a dilute polymer solution at a reference temperature, before and after heating, allows the thermal degradation of the non-Newtonian viscosity to be assessed. A dispersion of *n*-alkanes in water, proposed for energy storage and transport, is studied for viscosity (and heat capacity) behavior. Analytical works treat: the coupled flow and heat transfer in circular Couvette flow with temperature dependent viscosity and thermal conductivity; the influence of the thermo mechanical coupling, called the Piston effect, on heat transfer near the critical point; the effect of lubricant viscosity variation within the film on journal bearing performance; and the role of thermal history and viscosity for modeling the resin transfer moulding process [57P–63P].

17.9. Miscellaneous

Thermal properties are reported for a number of special systems: chicken-drum muscle over a wide range of muscle moisture content and temperature (Food Science); pressure-composition isotherms of high and low temperature metal hydrides; and heat transfer in the vicinity of an active volcano (New Zealand) [64P, 65P, 66P].

18. Heat transfer applications — heat exchangers and heat pipes

Heat exchangers and heat pipes and marked activity across a broad front of heat transfer applications characterize this section, particularly efforts made to enhance the heat transfer process by various techniques.

18.1. Compact and micro-heat exchangers

By experiment and numerical modeling investigators consider: the performance of a new swirl flow duct suitable for compact heat exchangers; the development of a CO_2 exchanger for automotive use and a miniature glass tube exchanger for low temperature service using nitrogen. Micro-heat exchangers are examined for future 3D electronics packaging systems, low hydraulic losses, forced liquid convection in rectangular channels, and the thermal resistance of flat plate designs [1Q–7Q].

18.2. Design

Contemporary developments in the thermal design (correlations, procedures and sizing) of finned-tube heat exchangers and the role of nonuniform overall heat transfer coefficients and flow maldistribution are examined. Crossflow exchangers are considered for indirect evaporative cooling, the effect of longitudinal wall conduction and minimization of entropy generation. Other works re-examine the Reynolds–Prandtl analogy between heat and momentum transfer in turbulent flow, analyze the relationship of temperature differences in heat transformation devices, and test an extended temperature oscillation measurement technique for determining the heat transfer coefficient. Analytical efforts treat hot-wall condenser and evaporate configurations in refrigeration appliances and a new condenser tube arrangement [8Q–19Q].

18.3. Direct contact heat exchangers

For gas–solid particle heat transfer: heat transfer coefficients have been measured and analyzed for radiation effects, and particle growth during chemical reaction. The efficiency of a direct-contact metal recovery condenser is modelled. For water sprays the parameters important in industrial spray cooling of a heated surface are observed and the evaporative cooling of air measured and simulated. Cooling towers are modeled and analyzed and for evaporators and absorbers, analytical works consider compact bubble absorber design, the evaporation process in a bubble column, and falling films in vertical tube evaporators [20Q–30Q].

18.4. Enhancement

An impressively large body of work explores, experimentally and numerically, geometrical, flow, and surface treatment approaches to promoting heat transfer. The experimental studies consider the use of louvered fins and hydrophilic coating to improve exchanger heat transfer; the effect of narrow, twisted, thin metallic strips, grooves in turn sections, triangular and pin fin arrays, corrugated–undulated exchanger surfaces and offset strip-fin exchangers. Other works study the benefit of elliptical pin fins in rectangular and circular ducts, develop experiment-based correlations for round tube and plate finned exchangers (28 exchanger samples tested), and examine the role of humidity in exchanger performance. Fin usage in a circulating fluidized bed and rectangular fin performance in free convection are also reported [31Q, 32Q, 35Q, 40Q, 41Q, 53Q, 54Q, 56Q, 61Q, 63Q, 64Q, 66Q–70Q, 72Q].

Another group of papers investigate specific systems of heat transfer enhancement techniques: swirl chambers and turbine blade cooling, roughened tube bundles, perforated baffles, air flow in contemporary compact exchangers (a review), rule of binary gas mixtures, and the influence of turbulence and flow rate variation. Also considered are mass transfer in a falling film absorber ($L1Br$–H_2O absorbers), use of vertical pinned plates in communication equipment, and manufacturing technology for plate-fins or pin-fins with extremely narrow pin pitch [34Q, 42Q–45Q, 50Q, 52Q, 55Q, 57Q, 59Q, 65Q].

Studies employing numerical analysis or modeling consider: laminar and mixed convective laminar flow in horizontal, internally finned tubes, laminar natural convection in enclosures with fins on active wall, and exchanger performance with fully — and partially — wet fin assembly. For finned oval tube, vortex generation is analyzed as are optimum dimensions for continuous plate fin with various tube arrays and forced convection — radiation heat transfer in the entrance region of internally finned tubes. Studies on louvered fin arrays in compact heat exchangers, transient heat transfer in annular fins and second-law analysis on wavy plate fin-and-tube exchangers conclude the analytical studies or enhancement [33Q, 36Q–39Q, 46Q–51Q, 58Q, 60Q, 62Q, 71Q].

18.5. Fouling — surface effects

Heat exchanger performance depends on the maintenance of clean surfaces. Efforts center on understanding the mechanism of fouling, preventive strategies, and remedies. Specific experiments consider the gravity effect on particle deposition on smooth surface, calcium carbonate ($CaCO_3$) scaling mechanism and kinetics, the fouling phenomena over a single tube in gas flow and the effect of thermophoresis on particle deposition (a simulation). Bacterial biofilms, their structure and properties, are reviewed and the use of biocides tested. Other approaches use wood pulp fibers, chemical cleaning (sugar refining), electronic anti-fouling technology, and study the effect of fouling on temperature measurement. Where fouling of surfaces is unavoidable design and optimum performance attempt to manage the problem. Thus plate exchangers in automotive use are reviewed for corrosion failures, frost growth on cooling surfaces modeled, the milk fouling of heat exchangers modeled are simulated, and an expert system devised for detecting fouling, optimum operating conditions and schedules predicted through a combination of fundamental studies, laboratory and plant measurements combined with models of the actual heat transfer process [73Q–92Q]

18.6. Mathematical modeling, optimization

Increasingly, mathematical models are developed to achieve optimum performance of heat exchangers. The MINLP model is applied to heat exchanger networks, one version allows the designer to specify beforehand desired topology features as design targets. Additional works solve the problem of maximizing mechanical power derived from a hot single-phase stream when total heat transfer area is fixed, use finite element simulation of transient laminar flow heat transfer for an in-line tube bank, and present a thermodynamic approach to a plate heat exchanger with a dispersive wave and the synthesis of optimal thermal systems. Other efforts model the heat and mass transfer of a ground heat exchanger, the cooling and dehumidification of air by a parallel, falling desiccant film, and the transverse heat transfer in thermoacoustics [93Q–102Q].

18.7. Performance, factors affecting

The works here cited examine the influence of certain factors on heat exchanger performance. Experimental works consider: flow-inducted vibrations for a high-temperature gas-gas exchanger with helically coiled tube bundles; nonplanarity (torsion) influence on convective heat transfer and friction loss for helical ducts of rectangular cross section; rotating drum heat exchanger (RDHE); oscillating flow effect on local heat transfer in a channel; and variable area heat exchangers. Analytical works focus on: countercurrent heat-transfer systems with three streams, perfect mixing and plug-flow conditions; thermoeconomic factors in design and rating of two-phase exchangers; radial fin assembly efficiency under dehumidifying conditions, and the development of mixed convection in a coiled heat exchanger. Additional efforts treat: falling-film NH_3–H_2O generators and absorbers; sub-slab heat exchanger for geothermal heat pumps; air conditioning coil performance prediction; thermoelastic stability of duplex heat exchanger tubes; and heat exchanger performance comparison for air-conditioning cycles using R-22 or CO_2 [103Q–117Q].

18.8. Reactors

Predominantly, investigations reported are numerical rather than experimental. Among the latter works there are papers on annular finned pyrolysers and their merit in promoting clean combustion of biomass materials, a calorimetric scheme for adjusting the mass of culture fluid in a bioreactor, the use of a multi-layer, packed bed, reactor in citric acid production, and a trickle bed reactor for hydrogenation of 2,4-dinitrotoluene. Other works consider temperature trajectories for well-mixed adsorptive reactors; the simulation of a full-scale pressurized bed combustor using pilot plant data; 'runaway' limits for adiabatic, packed-bed, catalytic reactors; and gas–solid, two-phase turbulent flow in fluid catalytic cracking riser reactors. The polymerizing reactor heat transfer for material (ethylene and methyl methacrylate) production is noted as are works on the modeling of reactors for photocatalytic oxidation of air contaminants and the passive residual heat removal in a natural convection heat exchanger for a nuclear reactor. Design tools and design parameter estimators are described as well as the modeling of catalytic processes [118Q–134Q].

18.9. Power and reversed cycles

The influence of heat exchanger characteristics on power and reversed cycle performance is analyzed in a number of studies. The closed Brayton cycle thermal efficiency is considered in one instance; in other cases thermal resistances and regenerative losses are examined for their influence on the performance of a magnetic Ericsson refrigeration cycle; and an air refrigeration cycle, and a model proposed to predict the performance of alternative refrigerants in vapor compression refrigeration/heat pump systems. The absorption refrigeration cycle, with losses, is analyzed for optimum performance and serves as a model to analyze a absorption heat transformer, and in another study a mathematical model is developed to predict performance of a vapor compression/liquid desiccant hybrid cooling and dehumidification absorber. The absorption process is employed in a number of ways: internally-cooled liquid desiccants cool and dehumidify, a hybrid liquid desiccant integrates evaporative cooling to achieve nearly isothermal operation, and non-absorbable gas presence in a falling film absorber influences chiller performance. A group of papers treat matters related to his section: matrix heat exchangers and energy recovery from liquid hydrogen, multi-stage flash desalination, regenerative monolithic rotor dehumidifier used for a absorption cooling, evaporative cooling of a falling water film on horizontal tubes, developing flow on heat transfer in laminar, oscillating pipe flow, and laminar flow and stratified chilled-water storage [135Q–152Q].

18.10. Shell and tube

Experimental investigations of local heat transfer coefficients on the outer surface of staggered tubes and in-line arrangement are accompanied by mass transfer measurements and the application of the analogy between heat and mass transfer. The effect of baffle spaging and leakage on pressure drop and local heat transfer are also observed. Fluid flow and heat transfer have been simulated using the distributed resistance concept. Inverting classical design, i.e. primary water flow in the shell side, secondary water in the tube bundle, reduces the collective dose to operators inside the exchanger channel head. A review article summarizes developments in conventional shell-and-tube and compact heat exchangers [153Q–162Q].

18.11. Thermosyphons (heat pipes)

Research on micro heat pipes includes the analysis of minimum meniscus radius and capillary heat transport limit and the re-evaluation of maximum heat transport capacity, as modeled by Cotter, in the light of current experimental data. Micro heat pipes processed as an integral part of semiconductor devices are also examined as an alternative to heat spreaders.

Experiments continue to explore the variety or applications of heat pipes: horizontal mantle exchangers in thermosyphon solar water heaters; heat pipes applied to turbine cooling in aircraft propulsion; liquid metal heat pipe performance during space shuttle flight and possible application to fusion processes; and rotating heat pipes using water and methanol. Additional works tested air-to-air exchangers according to HVAC guidelines and design methodology, observed the effects of transverse acceleration-induced body forces on the capillary limit of helically grooved heat pipes, and examined the similarity of the heat pipe to the non-isothermal constrained vapor bubble.

Analytical modeling is applied to: the startup characteristics of asymmetrical flat-plate and disk-shaped heat pipes; a network thermodynamic analysis of the transient behavior of device; the study of inclined, open thermosyphons; the simulation of a parabolic solar collector heat-pipe heat exchanger reactor for the dehydrogenation of cyclohexanes; and correlation for mixed convection heat transfer and pressure drop in tube-in-shell thermosyphon exchangers [163Q–178Q].

18.12. Miscellaneous

In the area of food science, spatial non-uniformity in microwave reheating is characterized, the electroconductive heating in solid- liquid mixtures investigated, and two continuous precrytallization process of chocolate compared. Other papers consider the role of integrated thin-film heaters in thermal crosstalk of laser arrays, compared DOE-2 predicted building energy flows with measurements on full scale structures and determined recombination and accommodation coefficients for oxygen atoms, important in calculating the energy release by spacecraft thermal protection during the atmospheric entry phase [179Q–184Q].

19. Heat transfer applications — general

The large number of papers in the subsections on meteorology and chemical processing of this section make a selection necessary. Papers are included, the emphasis of which is on the characteristics of the thermal energy transport processes.

19.1. Aerospace

The reentry aerodynamics are examined [7S] within wide ranges of angle of attack and flight attitudes by a Monte Carlo method. Three thermal protective systems (tile, blanket, metallic) are analyzed [12S] for reusable launch vehicles. A method is developed to study [11S] the ground effect on a delta clipper. Aeroassisted orbital transfer is optimized numerically [13S]. The performance of a folding heatshield reentry vehicle is investigated [9S]. Embedded cooling channels in the skin of an aircraft structure are investigated [4S]. The causes of unstart for ram accelerators are explained [6S]. Study projects assess [10S] an advanced heat shield concept. Experiments evaluate [1S] the performance of supersonic exhaust diffusers. The thermal properties of honeycomb core sandwich structures are analyzed [3S]. Brightness calculations for visible emissions from nitric oxide (the spacecraft glow) are presented [8S] for altitudes between 140 and 180 km. Fuel regression characteristics are measured [2S] in a radial flow hybrid rocket. A model describes [5S] the fluid drop behavior in a cluster of surrounding drops at rocket chamber pressure.

19.2. Bioheat transfer

A large number of papers were devoted to heating of various tissues. Thermal wave propagation [21S], laser radiation [26S] are considered. A generic convective equation describes energy balance in tissue [25S]. A two-compartment model estimates the temperature during general anesthesia [17S]. Thermal damage in cutaneous contact burns is predicted [24S] as in the shrinkage of collagenous tissue [16S]. Thermal models for transient temperature analysis are evaluated by comparison with experiments [19S]. Heat transfer in heat surgery is modeled [28S]. Heat and vapor transfer is computed [23S] in the human nasal cavity. Tissue temperatures during the removal of subcutaneous fat are determined [14S]. Heat Transfer during laser cutting of brain tissue is analyzed [31S]. Thermo regulation in the prostate during hermotherapy found attention [30S, 32S]. Water and aircooling are discussed [22S, 18S] in hyperthermia. A heat transfer model [27S] predicts safe touch temperatures of plates. Heat and moisture transfer is simulated in human clothing [20S]. The wind chill factor under predicts the chill temperature [15S]. A flexible algorithm constructs 3D arterial and venous networks [29S].

19.3. Electronics

Thermal characteristics of power-sensor Microsystems are studied [33S] by simulation and experiments. A transient thermal management strategy enables croblems in thermal simulation [34S]. An efficient thermal simulation is discussed [35S]. An experimental study deals with heat transfer enhancement in electronic modules varying secondary air injection hole arrangements [36S]. Hot spots by current crowding can be predicted [39S] in power transistors. Cooling characteristics of formed convection of flat form electronic components are studied [37S] in channel flow introducing adiabatic heat transfer coefficients. A finite element analysis studies the effect of moist air flow on the temperature prediction of a finite domain with source arrays [38S].

19.4. Piston engines

Heat transfer processes in the combustion chamber of direct-injection diesel engines are reviewed based on experiments in an atmospheric test rig [40S]. A finite element analysis studies heat transfer in diesel engines [44S]. A study assesses the effect of the overall heat transfer coefficient on optimal distribution of the heat transfer surface in a Sterling engine [43S]. Optimum cylinder cooling for advanced diesel engines is studied [45S] numerically and by experiments. Instantaneous unsteady heat transfer is calculated [41S] for a rapid compression engine. The optimal motion of a piston fitted in a cylinder in a cooling bath maximizes the expansion work [42S].

19.5. Gas turbines

Effect of squealer tips on rotor heat transfer and efficiency was calculated [46S]. A procedure for optimization of turbine blades is based on maximum blade temperature and on tangential force coefficient [48S]. Endwall heat transfer measurements were measured in a transonic cascade [47S].

19.6. Steam power plants

Heat transfer and combustion are simulated [50S] in a large tangentially fired utility boiler at the furnace exit. Deposition and corrosion measurements in a 10 MW straw fired boiler detected enhanced corrosion on heat transfer surfaces [49S].

19.7. Atomic reactor engineering

Recent advances in sensitivity analysis of nuclear reactors using perturbation methods are described [57S]. The Canadian algorithm [53S] covers postulated upset conditions in CANDU reactors. Experiments study [55S] core thermohydraulics under natural circulation conditions. The fuel pin temperature can be modeled using water [63S] and can be calculated [64S] by water reactor dynamics.

Post test calculations of noko experiments are described [60S] in the European research program. A linearized model is derived for the safe integral reactor [56S]. Analysis was performed for five accident sequences [52S]. Failure mode and effect analysis of the heat transfer system of a thermonuclear reactor was performed [58S]. Passive safety injection experiments are analyzed [62S] for advanced light water reactor and for a new AP 600 reactor [51S]. A code for best estimate of large break LOCA analysis was extended to an upper plenum injection plant [61S].

An experiment [54S] studies an ingress-of-coolant accident in fusion reactors. The fusion breeder with enhanced safeguarding capabilities against nuclear weapon proliferation is analyzed [59S].

19.8. Climatising

A computer code describes [68S] the performance of metal hydride heating/air-conditioning systems. A mathematical model characterizes the cooling of an evaporative cooler coupled to a room [72S]. Space cooling using metal ceiling panels is analyzed experimentally and analytically [66S]. Laminar air flow with low water-vapor concentration is cooled at temperatures well below 0°C to remove the humidity. This is studied experimentally and computationally [70S]. The infiltration load of air into a cold room through its doorways is modeled [69S]. A comparison of simulated and measured data is presented for three-dimensional earth contact of a buried structure [65S].

It is studied parametrically whether liquid desiccant can be used effectively to reduce energy consumed in air conditioning [71S]. Absorption chillers are generally considered inefficient. An entropy generation analysis study shows that the largest rate of entropy generation occurs in the beds of a silica gel–water chiller during the switching phase [67S].

19.9. Thermomechanical

A method is described by which the time can be calculated [76S] which is required for a steel structure to sustain the effects of a temperature rise prescribed by real fire curves. The concept of generalized modeling and control of thermal deformation of machine tool structures is described [73S] and studied [74S] using generalized transfer functions. The yield limits of plates at heat fluxes of order 10 MW/m^2 are predicted by a calculation of the elastic stresses [75S].

19.10. Meteorology

A model for weather prediction represents the effects of hills on temperature and moisture in the atmospheric boundary layer [79S]. A heat and water model simulates [77S] the surface energy fluxes and surface temperatures in soil vegetation atmosphere transfer and studies [81S] the effect of soil thermal conductivity. An ice–ocean model is developed and applied to the Hudson bay [83S]. Spaceborne thermal emission and reflection radiometer measurements are used to estimate energy fluxes from the land surface [84S]. Thermal boundary layer and stagnant lid convection analyses with non-Newtonian viscosity are used to calculate [82S] mantle convection on Mars and Venus. Studies on the thermal evolution of permafrost predict [86S] the retreat of alpine glaciers. The German continental deep-drilling program was used to study heat transfer processes in the deep continental crust [80S]. Detailed thermoalkaline water pathways were calculated [87S] and found consistent with observations in the Mediterranean sea. A new method computed [78S] surface transfer coefficients based on state-of-the-art empirical flux profile measurements. A biosphere model is coupled to a global dynamic model to study the climatic impact of land surface operations [85S].

19.11. Manufacturing

Mathematical modeling is applied more and more to manufacturing processes whereas the number of experimental studies remains relatively small.

Many aspects of tribology of hot metal forming need clarification [89S]. Cooling systems, cooling rates, transient mold temperatures, and simulation of the filling stage are discussed [105S, 106S, 94S, 93S]. Heat transfer in forging [95S, 96S] is simulated, heat release, temperature, velocity are modeled in smelting [102S, 103S]. Thermal transport in optical fiber drawing is clarified [108S, 91S, 92S]. Continuous sheet casting and strip casting are modeled [101S, 90S]. Friction welding [100S] arc welding [107S], and hot plate welding [99S] are objects of investigation. Publications deal with cold and hot rolling [98S, 104S]. Experiments clarify heat transfer and life of metal cutting tools [88S] and of the peel and powder in grinding [97S].

19.12. Chemical processing

Synthesis of a heat exchanger network develops a systematic procedure to find an optimal network and heat transfer areas to meet target temperatures at minimum cost [122S]. Unsteady calculations are capable to predict [121S] the detailed deposition profile even in the inlet region of a chemical vapor deposition process. An investigation of membrane distillation with a laminar flow of the streams in a module has been performed [115S]. An analysis studies [114S] the problem of heat generation in a fluid flowing through a pipe of finite length and the development of thermal runaway. Inverse and predictive control systems are applied [113S] to the real-time control of the heat transfer fluid temperature in a pilot chemical reactor. The effect of surfactant monolayers on heat transfer through air/water interfaces is studied by observing changes in the surface temperature [112S]. Impulse drying was simulated [118S] with a platen press equipped with a heated pressing head. A two-dimensional model was developed [119S] for the reacting gas flow, heat transfer and electro dynamics in the discharge reactor for diamond film deposition. The non-linear equations based on moments of the aerosol size distribution function are solved asymptotically for aerosol reactors [124S]. The fundamental heat transfer processes in multi-zone batch furnaces are analyzed [111S]. The numerical solution of current and temperature distribution in a solid oxide fuel cell can be simplified significantly by analogy with modeling of radiative heat transfer in packed bed reactors [117S]. The deposition of thin solid films in CVD processes is determined by hydrodynamics, chemical kinetics, and transport phenomena and modeled [123S] to study the influence of an electric field. Heat transfer and deposition rate in an CVD process are modeled [116S] as a buoyant jet flow impinging on a circular cylinder. The analysis of heat transfer during sterilization and cooling of a cylindrical canned product is presented [110S]. The application of transfer functions in foods for heat and mass transfer problems was the subject of several studies over the last decade [120S]. A model for the prediction of temperature profiles in a microwaved dough was developed [125S]. A finite element method to solve the unsteady heat transfer equations describing the heating of turkeys in a conventional electric oven was developed [109S].

20. Solar energy

Papers are broadly divided into low-temperature solar applications, high-temperature solar applications, and energy use in buildings. Papers on solar energy or energy conservation that do not primarily focus on heat transfer, for example, papers on photovoltaics, wind energy, architectural aspects of building design and control of thermal systems, are excluded.

Low temperature solar applications include domestic water heating, space heating and cooling, desalination of water, and solar ponds. Within this category, papers on non-concentrating solar thermal collectors and thermal storage are discussed.

High temperature solar thermal applications require use of concentrated solar energy. Uses include electricity generation, thermochemical reactions and industrial process heat. Papers address processes as well as system components such as heliostats, concentrators, and receivers/reactors.

The section on energy use in buildings includes papers on characterization of energy use and heat transfer in building components.

20.1. Low temperature applications

20.1.1. Flat-plate and low-concentrating collectors

Conventional flat-plate liquid solar collectors are a mature technology. The only paper that adresses heat transfer in a traditional geometry is an experimental study of wind-induced losses. Convective heat transfer coefficients from a heated surface mounted onto a roof were in good agreement with previously published correlations [7T].

Studies of air collectors include numerical analysis of the use of porous substrates [1T], optimization of the shape of triangular absorbers [4T], and a model of transient heat transfer in a rectangular vertical channel [5T]. A relatively new concept for solar air heating is to preheat ventilation air by cooling photovoltaic modules on ventilated facades and roofs [6T].

Two studies address heat pipe solar collectors. Experimental analysis of a heat pipe solar collector that uses R11 shows the effects of tilt angle, and design of the condenser and wick on thermal performance [2T]. [3T] compares outdoor performance of a heat pipe collector with methanol to a conventional liquid collector.

Collectors that combine collection and water storage are discussed in Section 20.1.2 [10T].

20.1.2. Water heating

Papers in this category deal exclusively with domestic water heating, specifically use of photovoltaic pumps, design of collectors with integrated storage, thermal stratification and fluid mixing in water storage tanks, and heat exchanger performance. [8T] provides a practical method for selection of the components of a photovoltaic pumping system (motor, PV cells and pump) to optimize system performance. A nomogram based on dimensionless parameters is developed for predicting performance of integrated collector storage (ICS) systems [10T]. Thermal behavior and fluid dynamics of water storage tanks are examined in [9T], [11T] and [12T]. [9T] considers the effect on entrainment and diffusion of location of the inlet and outlet ports. The numerical study of Hahne and Chen [11T] characterizes thermal stratification with Richardson and Peclet numbers. A three-dimensional model of a vertical mantle tank/heat exchanger is validated and used to develop a Nusselt–Rayleigh correlation for natural convection heat transfer. [13T] presents experimental data for a load-side heat exchanger used with an unpressurized drain-back system.

20.1.3. Space heating

Most work on solar air heating addresses design of the collector. Those papers are discussed in Section 20.1.1 [1T, 4T, 5T]).

A model of a solar driven heat pump is presented by Wu et al. [15T]. Inalli [14T] models a community solar heating system with a large underground storage tank. Emphasis is on ground temperature distribution.

20.1.4. Space cooling

Data on enhancement of heat transfer and more effective absorption/desorption using a zeolite-active carbon is presented by Loiu et al. [18T]. Performance of an ammonia–water storage combined with a heat pump that uses the ammonia mixture as the refrigerant is compared to an eutectic salt storage system [21T]. A comparison of double- and single-glazed lithium-chloride solar systems operating in Taiwan is presented along with heat and mass transfer correlations useful for design [23T].

Papers that address cooling applications in buildings include a control strategy to minimize operating cost and energy use of ice storage systems [17T], modeling of heat transfer through a spray cooled roof [16T], and simulation of an attic radiant barrier [20T]. A transient heat and mass transfer model of radiant barrier retrofits indicates that emissivity is the most significant parameter [19T].

[22T] presents a model of solar desiccant cooling for aeration of stored grains.

20.1.5. Storage

This section includes papers that specifically address storage. Papers that address the use of storage as part of domestic water heating [9T, 11T, 12T] or space cooling systems [17T, 21T] are discussed in the sections on those applications.

[25T] gives an economic analysis of sensible heat storage. [24T] presents a generalized model to determine the optimum phase change temperature for latent storage. [26T] considers the effect of geometry on the transient behavior of phase change material. In one geometry, the material is packed in cylinders and the heat transfer fluid flows parallel to the cylinders. In the second geometry, pipes containing the heat transfer fluid are embedded in the storage material. Optimal geometric design is discussed in terms of material, flow rates and temperatures. Measurement of heat extraction from ammonium alum and ammonium nitrate encapsulated in polyethylene balls packed in a cylindrical bed through which air passes indicate that the Stanton number is increased by 74% for sensible heat extraction [28T].

Storage in buildings is the subject of [27T, 29T, 30T]. The effect of thermal storage walls (Trombe walls) on air temperature and movement are studied numerically by Gan and Khalifa [27T, 29T]. [30T] models heat transfer of air flow through a hollow core concrete slab.

20.1.6. Desalination

Studies of conventional single basin solar stills model the effect of the slope of the cover [31T] and measure the overall heat transfer coefficient between water and glazing [34T]. Two groups considered preheating of the saline feed water. [32T] circulated air in a closed-humidification–condensation cycle. Productivity of the still was improved at low air temperatures [32T]. Mink and Karmazsin [33T] were able to achieve a three-fold increase in yield in an air blown still with heat recycling.

20.1.7. Solar ponds

In their presentation of a model of heat and mass transfer in a shallow pond for green house aquaculture, [36T] provides insight on the use of polyethylene and polyvinyl chloride glazing as opposed to low emissivity glass. [35T] models the effect of load on the thickness of the non-convective zone in a traditional pond.

20.2. High temperature applications

Papers address design of the concentrating system, including heliostats, parabolic troughs and solar towers, receiver/reactors for thermochemical processes, and heat engines. [37T] discuss the upper bound for the efficiency of converting solar energy into work. Yogev et al. [46T] provide an overview of high temperature solar systems and give a promising economic analysis. [38T] models the efficiency of a solar Stirling engine system. Kribus et al. [42T] derive upper limits on the performance of an axis-symmetric heliostat field, a solar tower, secondary optics and black receiver. The tower-top cone provides the best concentration and efficiency. The suitability of different design options is presented. Odeh et al. [43T] model direct stream generation in parabolic trough collectors. They compare current technology that uses synthetic oil in the collectors to use of water. Tchinda et al. [45T] model transfer heat in the CPC collector. Construction and behavior of vacuum glazing is reviewed in [39T]. Emphasis is on vacuum stability and mechanical strength.

Thermochemical reactions and reactor/receivers are the topics of three papers. Ries et al. [44T] model a decomposition reaction of a solid particle into solid plus gas in an open receiver. They derive the criteria for reaction stability and give the limits of stable operation. For many applications, a transparent window is required. Design of the 'window' is a challenge because of the high temperature and pressure usually demanded. Karni et al. [40T] present a frustrum-like design made of fused silica. Optical, mechanical and thermal analysis as well as experimental data indicate satisfactory performance at 30 bar and 1700°C. Extended evaluation of the novel 'Porcupine' absorber in the solar furnace at the Weizmann Institute provide evidence of its endurance at high flux [41T].

20.2.1. Buildings

Papers in this area are subdivided into modeling of energy use and HVAC systems, measurement and interpretation of energy data, and development and characterization of building components.

Modeling of hourly energy requirements and HVAC systems is the subject of [49T, 52T, 56T, 58T, 62T]. [49T] addresses building heat storage in an urban environment where adjacent buildings, street level use and enclosed air volume affect heat fluxes. Numerical experiments examine the importance of various parameters. Multiple linear regression is used to predict hourly energy consumption in commercial buildings [58T]. Accuracy of multiple and linear regression models of cooling energy use for two commercial buildings are compared. The same group from Texas A&M University model hourly energy use with Fourier series functional forms [52T]. [56T] discusses procedures for calibrating building energy simulation models like DOE2. A calibrated model is used to optimize HVAC operation in 18 buildings with a potential savings of two million dollars annually [62T]. Regression analysis [59T, 65T] and neural network [60T] models of energy saving are presented. [50T] uses DOE 2 to categorize the construction characteristics of the building envelope to the cooling load in sub-tropical climates.

Measurement techniques and data interpretation are discussed in [47T, 51T, 53T–55T]. A review of the methods used to analyze measured energy use in commercial buildings is given by Claridge [51T]. Development of graphical indices for displaying data are reviewed and illustrated in two papers [54T, 55T]. An algorithm to disaggregate hourly electrical load into hourly load profiles for air conditioning, lighting fans and pumps is presented and applied to data for Department of Defense facilities [47T]. A method for detecting and evaluating thermal flaws in buildings uses transient thermographic measurements of temperature [53T].

Analysis of heat transfer in building components is the subject of papers on window glazing [48T, 63T, 57T], and slab floors [61T, 64T]. Work on radiant barriers is discussed in the section on solar cooling see [19T]. [48T] uses a transient one- dimensional analysis to evaluate conductive, convective and radiative heat transfer in laminated glazing with chemically deposited solar control coating. CFD models and flow visualization of diffusion, convection and radiation is double pane windows with a screen and a semi-open cavity for thermal siphon are used to develop a Nusselt number correlation [63T]. Ismail et al. [57T] present a two-dimensional model of a double pane window filled with phase change material. Krarti and Piot [61T] present a steady-periodic solution of conduction under a slab floor adjacent to another slab. Insulation for floors made of a polyethylene pacing waste is investigated by Megari et al. [64T].

21. Plasma heat transfer and magnetohydrodynamics

21.1. Plasma fluid flow characterization

Several new models have been presented describing specific aspects of plasma nozzle flows. Capitelli et al. [1U] have determined the electron energy distribution function for expanding nitrogen arcs based on solutions of the Boltzmann equation and have found a strong effect of excited state densities. A two-dimensional, two-temperature viscous flow model of a supersonic hydrazine arcjet has demonstrated the thermal and chemical non-equilibrium in such a plasma and the effect of ionization and excitation on the anode attachment location [9U]. A similar configuration has been modeled by Jodoin et al. [7U] including the non-equilibrium cathode sheath. A model of a subsonic dc plasma torch using the PHOENICS code with the *k*–epsilon turbulence description, but assuming thermal and chemical equilibrium, has provided temperature and velocity profiles for an argon — hydrogen plasma flow and shows the effects of entrainment of an ambient gas [4U]. A new theoretical approach for the description of flows of fluids which are in far-non-equilibrium has been presented by Itoh and Itoh [6U], with special treatment of the non-linear turbulence effects. The fluid dynamics and heat transfer in an argon–hydrogen radio frequency induction plasma torch have been modeled by Chen et al. [2U] incorporating a combined-diffusion-coefficient approach, and the effects of a central injection probe and of varying central flow rates are described. Another model of a similar rfi plasma reactor has concentrated on determining the mixing patterns between the central helium or nitrogen flow and the hydrogen sheath gas, and the results are compared with those from enthalpy probe measurements [3U]. A report of an experimental study of the plasma flow generated by a magnetoplasmadynamic generator in a reentry simulation describes the results of electrostatic probe measurements [5U]. Electron density and temperature distributions have been derived and plasma velocities have been determined from the time of flight measurements of natural perturbations in the plasma. In another experimental study, the production of atomic nitrogen in a rectangular microwave plasma generator has been investigated using emission spectroscopy, and it has been found that 3.3% of the absorbed power is transformed into dissociation energy [11U]. An accurate model prediction of the characteristics of a low pressure parallel plate plasma reactor operating with nitrogen is presented by Longo et al. [8U], and it has been shown that a self-consistent treatment of the plasma dynamics together with the non-equilibrium molecular kinetics is necessary. Menart and Lin [10U] present a model of a free-burning argon arc including the cathode, and they point out the effect of the selection of a length scale in the radiation treatment using net emission coefficients.

21.2. Plasma–solid interaction

The arc–cathode interaction is modeled in two papers. One of them describes the supersonic hydrazine arcjet configuration [16U] with two different approaches, and with the results from an arcjet model [9U] as an input and the results giving sheath voltage and electron temperature and density distributions. The second model attempts to explain the observed different attachment modes on thermionic cathodes (diffuse or filamentary) with a non-uniqueness of the solutions of a multidimensional thermal balance with non-linear external energy fluxes [13U]. An experimental investigation of the arc cathode interaction is reported by Zhou and Heberlein [19U] including temperature and electron density data in front of the cathode and cathode surface temperatures for different operating conditions. A numerical anode heat transfer analysis presented by Amakawa et al. [12U] describes the abrupt change in fluid flow and heat transfer characteristics between an arc and the anode when the flow velocity in the direction of the anode surface, i.e. the boundary layer thickness is altered. Two further papers describe the heat transfer from a plasma flow to a spherical particle [14U, 18U] as function of plasma and particle parameters. The heat transfer from a low pressure (1 torr) rf plasma to a surface in a plasma CVD reactor has been modeled [15U], and the resulting temperature profiles have been compared with those obtained from CARS measurements. The results allowed the determination of thermal accommodation coefficients for different gas/surface combinations and for different pressures. The effect of an ultrafast laser pulse on the crystal structure of a GaAs crystal has been investigated in [17U], and the results have been explained by heat transfer from a plasma filling the laser induced crater.

21.3. Plasma applications

Experimental results from a high power electric discharge launcher have been used to derive plasma temperatures (23–35 kK), and gas heating efficiencies have been found to increase with the initial gas pressure reaching 90% for starting pressures of 40 MPa [24U]. Elnaas et al. [20U] have investigated the plasma synthesis of calcium carbide in a spouted-fluidized bed reactor operated with argon and hydrogen, and have concluded that this plasma process offers a more efficient alternative for calcium carbide production. An interactive flow visualization program has been developed for plasma spraying applications, based on solutions from the LAVA code, and it has been used for showing transient effects on temperature and pressure distributions and particle flows [22U]. Measurements on an aluminum welding process have shown arc heating efficiencies of 48–66%, increasing with voltage and decreasing with increasing current, and the different heat transfer mechanisms from the arc to the workpiece have been critically examined [21U]. An analysis of the effect of pulsing on the droplet transfer rate in arc welding with a consumable electrode is presented by Nemchinsky [23U] showing that a high pulse frequency leads to a lower thermal load on the weld and lower metal fume formation.

21.4. Magnetohydrodynamics

Several models deal with special boundary conditions for MHD flows. The three-dimensional flow and heat transfer characteristics of the MHD flow at a transpiration cooled stagnation point are modeled using a similarity solution for the boundary layer [27U]. Another model describes the effect of suction and blowing on the flow and heat transfer of a MHD flow over a vertical stretching surface [28U]. The effect of blowing rate and magnetic fields on the boundary layer for an MHD flow over a wedge is presented by Kumari [32U] using an implicit finite difference scheme. In another calculation of unsteady flow, the effect of surface temperature oscillations on the heat transfer to or from a free convection MHD flow along a vertical plate has been determined using a linearized theory [30U]. A new modeling approach for supersonic MHD channel flow is presented by Harada et al. [29U] using a fourth order modified Runge–Kutta scheme augmented with total variation diminishing models.

The effect of magnetic fields on the stability of liquid metal flows across a cylinder has been investigated by Mutschke et al. [33U], and it has been found that strong fields can stabilize 2D flow and suppress vortex shedding. A similar configuration has been investigated theoretically and experimentally by the same group [38U] using an electrolyte solution flow across a cylinder. Flow visualization and modeling results have been used to demonstrate the effects of the electromagnetic forces. The pressure drop and heat transfer from a gas–liquid metal two phase flow in a rectangular channel have been calculated using an annular configuration model, and the results have shown that lower pressure drops and increased heat transfer can be expected compared to single phase liquid metal flow [31U]. The pressure drop and heat transfer characteristics for liquid lithium flow and helium–liquid lithium two phase flow have been experimentally determined for rectangular and circular channels by Takahashi et al. [36U, 37U], and the changed convection heat transfer due to changed flow patterns is described.

A numerical model for the flow and heat transfer characteristics of a non-Newtonian flow in an eccentric annulus is presented by Ahmed and Attia [26U]. In two papers the effect of radiation in MHD flows is presented. Raptis and Massalas [34U] use the Rosseland approximation to describe the radiative flux from a gray medium, while Abbey and Mbelegu [25U] assume an optically thin medium but consider slip flow conditions caused by high temperatures rather than low pressures.

The effect of gas pressure on the efficiency of a MHD accelerator has been studied experimentally by Sherbakov [35U] using supersonic air flow seeded with KNa eutectic, and flow characteristics have been found to be insensitive to the pressure increase. The effect of an axial magnetic field on the heat transfer in a potassium vapor heat pipe has been investigated by Zarkova and Guerassimov [39U], and it has been found that the measured heat flux decreases as a result of the magnetic field.

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