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Review

Heat transfer—a review of 2002 literature

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1. Introduction

Heat transfer continues to be a field of major interest to engineering and scientific researchers, as well as designers, developers, and manufacturers. Considerable effort has been devoted to research in traditional applications such as chemical processing, general manufacturing, energy devices, including general power systems, heat exchangers, and high performance gas turbines. In addition, a significant number of papers address topics that are at the frontiers of both fundamental research and important emerging applications, such as microchannel flows, bio-heat transfer, electronics cooling, semiconductors and a number of natural phenomena ranging from upwelling currents in the oceans to heat transport in stellar atmospheres.

The present review is intended to encompass the English language heat transfer papers published in

2001. While being exhaustive, some selection is necessary. Many papers reviewed herein relate to the science of heat transfer, including numerical, analytical and experimental works. Others relate to applications where heat transfer plays a major role in not only virtually all man made devices, but natural systems as well. The papers are grouped into categories and then into sub-fields within these categories. We restrict ourselves to papers published in reviewed archival journals.

Besides reviewing the journal articles in the body of this paper, we also mention important conferences and meetings on heat transfer and related fields, major awards presented in 2002, and books on heat transfer published during the year.

The 5th ISHMT-ASME Heat and Mass Transfer Conference was held in Calcutta, India, on 3–5 January. Topics covered included microscale heat transfer, and droplet heat transfer. The 2nd Mediterranean Combustion Symposium on 6–11 January discussed flame structure and modeling, fires and explosions, and turbulent combustion modeling. A meeting on Thermal Challenges in Next Generation Electronic Systems held in Santa Fe, USA, on 13–17 January discussed, among other subjects, challenges in micro- and nanoscale transport, and novel thermal management concepts. HEFAT 2002—The 1st International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics was held in Mpumalanga, South Africa on 8–10 April. The International Center for Heat and Mass Transfer (ICHMT) organized the 2nd International Symposium on Micro/Nanoscale Energy Conversion and Transport (MECT'02), on 14–19 April, in Antalya, Turkey. A meeting on Visualization and Imaging in Transport Phenomena was held in Antalya, Turkey, on 5–10 May. The ASME Turbo Expo 2002 organized by the International Gas Turbine Institute was held in Amsterdam, the Netherlands on 3–6 June. Sessions in heat transfer discussed film cooling, internal cooling, and transitional flows in turbomachinery. SOLAR 2002, a meeting on solar energy was held in Reno, USA, on 15–20 June. Topics covered included non-tracking collectors, parabolic trough collectors, solar ponds, and solar cooling and refrigeration. The 8th Joint AIAA/ASME Thermophysics and Heat Transfer Conference held in St. Louis on 24–27 June discussed, among other topics, laminar and transitional flows, hypersonic flows, flows with reactions, and microchannel heat transfer. The 12th International Heat Transfer Conference was organized in Grenoble, France, on 18–23 August. Papers were presented on heat transfer under non-equilibrium conditions, heat transfer in non-homogeneous media, and general applications. The International Mechanical Engineering Congress and Exposition (IMECE) 2002 was held in New Orleans, USA, on 17–22 November. The Heat Transfer Division of ASME organized sessions on, among other topics, thermophysical properties of nano- and microscale materials and thermal issues in their fabrication, transport phenomena in fuel cells, and spray and droplet heat transfer.

The 2002 Heat Transfer Memorial Awards were presented to Massoud Kaviany (Science) for his research on heat transfer in porous media, to J.-C. Han (Art) for his contributions in the area of heat transfer in internal cooling of gas turbines, and Roop Mahajan (General) for his successful use of neural networks for thermal modeling, and advancing the state of knowledge of transport phenomena in high-porosity foams. Dr. John Chen was awarded the 2001 Max Jakob award at the 12th International Heat Transfer Conference for his contributions to the theory and practice of boiling heat transfer, particularly convective and dispersed-flow film boiling in tubes, and falling-film evaporation outside of tubes. The 2002 Luikov medal was given to Dr. Alexander Leontiev for his work on mass transfer.

Books on heat transfer published in 2002 include:

Computational Heat Transfer
Y. Jaluria, K. E. Torrance
Taylor & Francis, Inc.

Heat Transfer: A Practical Approach
Y. Cengel
McGraw-Hill Inc.

Transport Phenomena for Chemical Reactor Design
L.A. Belfiore
John Wiley & Sons, Inc.

Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics and Heat Transfer
M.J. Moran, H.N. Shapiro, B.R. Munson, D.P. DeWitt
John Wiley & Sons, Inc.

Fundamentals of Thermodynamics (6th edn.)
R.E. Sonntag, C. Borgnakke, G.J. Van Wylen
John Wiley & Sons, Inc.

Thermodynamics and Statistical Mechanics
J.M. Seddon, J.D. Gale
John Wiley & Sons, Inc.

Convective Heat Transfer (2nd edn.)
T. Cebeci
Springer-Verlag, Inc.

Heat Transfer in Single and Multiphase Systems
G.F. Naterer
CRC Press

Advances in Heat Transfer (Vol. 36)
J.P. Hartnett (ed.)
Elsevier Science and Technology

Energy and Society: An Introduction
H.H. Schobert
Taylor & Francis, Inc.

Inverse Engineering Handbook
K.A. Woodbury
CRC Press

Design and Simulation of Thermal Systems
N.V. Suryanarayana, O. Arici
McGraw-Hill Inc.

Radiation Heat Transfer: A Statistical Approach
J.R. Mahan
John Wiley & Sons, Inc.

Hydrodynamics, Mass and Heat Transfer in Chemical Engineering
A.D. Polyanin, A.M. Kutepov, D.A. Kazenin, A.V. Vyazmin (eds.)
Taylor & Francis, Inc.

Solar Energy: Fundamentals, Design, Modelling and Applications
G.N. Tiwari
CRC Press

Biological and Bioenvironemental Heat and Mass Transfer
A.K. Dutta
Marcel Dekker

Transport Phenomena and Unit Operations: A Combined Approach
R.G. Griskey
John Wiley & Sons, Inc.

Heat Exchangers: Selection, Rating and Thermal Design
S. Kakac, H. Liu
CRC Press

Industrial Mathematics: Case Studies in the Diffusion of Heat and Matter
G. L. Fulford, P. Broadbridge
Cambridge University Press

Extended Surface Heat Transfer
A.D. Kraus, A. Aziz, C. L. Ratner, M. Nissenbaum, G. M. Pape
John Wiley & Sons, Inc.

Propellants and Explosives: Thermochemical Aspects of Combustion
N. Kubota
John Wiley & Sons, Inc.

Thermal Energy Storage: Systems and Applications
I. Dincer, M. Rosen
John Wiley & Sons, Inc.

Extended Surface Conjugate Heat Transfer
P. Heggs, S. Harris, D.B. Ingham
John Wiley & Sons, Inc.

2. Conduction

The heat transfer review in 2002 in the category of heat conduction has approximately 75 archival articles ranging across a broad range of themes. The various sub-categories include: contact conduction/contact resistance; microscale/nanoscale heat transport, non-Fourier heat transport models, heat waves and pulse heating; heat conduction in complex geometries and composites and layered media; analytical/numerical methods and simulations; experimental and/or comparative studies; Thermal stresses and thermo-mechanical aspects; and miscellaneous applications of heat conduction studies. The relevant details of the various sub-categories are listed below.

2.1. Contact conduction/contact resistance

The studies in this category specifically deal with effect of diamond coatings on carbide substrates [1], contact conductance and constriction effects on non-flat coated metals,change of scale effects, interface effects due to random disk contacts, size and located contacts [2–5], coated joints [6], and heat transfer through periodic macrocontact constriction [7].

2.2. Microscale/nanoscale heat transport, non-Fourier effects and laser/pulse heating

Most notably, this has been a topic area of utmost research activity and increased interest with the dawn of the new century. A variety of experimental techniques, theoretical models and simulation techniques have evolved attempting to explaining the aspects of heat transport mechanisms at different length scales with emphasis on the micro/nano length scale. The theoretical models seek to formulate new models and/or use existing models with modifications with the arguements that the classical continuum theories such as the Fourier model cannot explain the heat transport mechanisms at small length scales. Although the alternate approaches which are primarily based on approximations emanating from the Boltzmann transport equation (BTEA) do seem to provide reasonable agreement with experimental data(mostly in the context of applications to dielectric materials), they need a few fitting parameters (such as some idea of the bulk material property, the issue of approximating the elusive relaxation times, etc.) to correlate the results. Nonetheless, there is no convincing evidence that the arguements provided to resort to these alternate microscopic energy transport models is necessary since literature in previous years and/or more recent efforts at the time of preparing this review strongly provides arguements to the contrary and the reader is urged to carefully dwell into the details to understand the pros/cons. Alternately, molecular dynamics simulations exist in the literature and avoid the notion of fitting parameters; however, they lack the ability to model realistic practical situations as of this date (high performance computing platforms and computational tools may provide some relief to model more meaningful size applications in the years to come). Finally, experimental results are indispensible but critical studies need to be conducted for repeatability of results and understanding the limitations/assumptions employed is also an important aspect. Both space scale effects and time scales are critical in bridging the multiscale aspects for understanding heat transport.

The various studies this year included short-pulse laser heating effects [8–10]; hyperbolic heat conduction and thermal waves [11–14]; constitutive models arguing the inability of classical models to model heat transport at small scales (certain of the issues are only being recently challenged) in space and time [15–17]; studies at interfaces and contacts [18–20]; and other analysis methods [14,21].

2.3. Heat conduction in complex geometries, composites/layered media and fins

The studies in this sub-category included time-dependent heat transfer in a fin-wall assembly and two-dimensional pin fins with non-constant base temperature [22,23]; multidimensional layered bodies [24], layered infinite media [25], a spreadsheet solution for composite fins [26], and a boundary integral approach for composite media [27].

2.4. Analytical/numerical methods and modelling/ simulation techniques

As in previous years, there has been continued interest and activity in this sub-category. The topics range from new developments in analysis and numerical methods and tools, application of numerical methods to studying heat transport for a variety of applications and the like. The numerical techniques include FD, FE, BEM, lattice Boltzmann methods, differential transforms, spectral methods, and the like. The various papers appear in [28–47].

2.5. Experimental studies

An experimental study on thermal writing and nanoimaging with a heated atomic force microscope cantilever appears in [48]. A comparative experimental and numerical study on a miniature Joule–Thomson cooler for steady-state characteristics appears in [49].

2.6. Thermal stresses and thermomechanical problems

This subcategory deals with the multiphysics issues of the fusion of heat conduction and elasticity under the umbrella of thermal stresses. The studies include isotropic circular fins [50], cryogenic liquid rocket engines [51], annular fins [52], numerical studies using BEM [53], and temperature and stress fields in silver using laser picosecond heating pulse [54].

2.7. Miscellaneous applications

A wide range on a variety of topics in heat conduction and application areas have also appeared in the literature [55–73].

3. Boundary layers and external flows

Papers on boundary layers and external flows for 2002 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 or property effects and flows with reactions.

3.1. External effects

Experimental results which document the effects of freestream turbulence on heat transfer from plates were reviewed [74]. Disparities in results from various references were addressed. Enhancement by turbulence generated by ultrasonically induced gaseous cavitation in CO_2-saturated water was experimentally documented [75]. The enhancement comes from destroying the viscous sublayer. The effects of turbulence integral length scale on heat transfer from a circular cylinder in crossflow were measured [76]. The average heat transfer coefficient changed very little with the length scale change, relative to the changes with turbulence intensity.

The effects of streamwise steps in wall temperature and roughness on changes in origin of turbulent thermal boundary layers were measured [77]. A model was presented for evaluating fluxes of mass or thermal energy in urban boundary layers [78]. The naphthalene sublimation technique was employed to evaluate the model. The results showed that street ventilation is less sensitive to depth of the street canyon when the flow is in equilibrium with the urban surface (developed). Enhancement of heat transfer with Goertler vortices on a concave surface was experimentally determined [79]. Steady growth of the vortex structures induces a characteristic plateau in the evolution of Stanton number versus Reynolds number, until transition. The effects of a pair of longitudinal streamwise-oriented vortices were measured [80]. Liquid crystal thermometry was employed. The region of common down-flow has higher heat transfer rates than the region of common up-flow. Non-linear instability of the cylindrical interface between the vapor and liquid phases of a magnetic fluid was analyzed with a method of multiple time scale expansion [81]. The region of stability was displayed graphically.

3.2. Geometric effects

Experiments and flow visualization were conducted for the problem of forced convection heat transfer with inclined and yawed round tubes [82]. It was shown that the sensitivities to yaw and angle of attack were very small. Experiments were conducted on a circular cylinder in cross-flow with non-isothermal blowing through the wall [83]. The effects of blowing on instabilities in the wake were described and modeled. A conjugate heat transfer analysis was conducted for a vertical cylinder with heat generation and axial conduction [84]. The radial temperature distribution was shown to have a significant effect. Heat transfer from two circular cylinders in cross-flow was analyzed [85]. Effects of the placement geometry were discussed. Measurements were made of scalar transport in the region where a turbulent wake interacts with a boundary layer [86]. Measurements included instantaneous values of two components of velocity and temperature. The effects of a wall on heat transfer from a microcylinder near a wall were studied numerically [87]. Applications include corrections for wall effects on hot-wire anemometry. Measurements were made of heat transfer around a circular cylinder/plate combination [88]. The plate was either flat or curved. Visualization documented the flow around the cylinder. A model for describing the combined free and forced convection boundary layer flow in a corner was presented [89]. The existence of two streamwise symmetrically disposed vortices in layers immediately adjacent to the corner layer was noted. The effects of vortices on a surface with dimples in supersonic flow were measured [90]. The hollows not only intensify heat transfer by also decrease recovery equilibrium temperature coefficients. Heat transfer over a slot-perforated flat surface was theoretically studied [91]. The external stream was pulsated, which led to a disturbance in the boundary layer attributed to the presence of the slot. Liquid crystal thermometry was used to document the effects on heat transfer of surface-mounted obstacles of circular, square and diamond shapes [92]. The effects of number and orientation on the surface were also documented. Optimization of rib-roughened surface geometries was conducted numerically [93]. The objective was to determine the best geometry while considering heat transfer and drag. Experiments were conducted to assess Reynolds analogy for rough surfaces [94]. Numerical simulations were conducted for describing roughness effects on heat fluxes with high winds over the sea [95]. Applications include simulations of hurricane conditions. Theory and experiments were applied to describing stationary vortices in Karman grooves [96]. The feasibility of holding the vortices within the grooves was studied. When the vortices were within the grooves, they were stationary and in the "persistent regime of turbulent fluxes". Displacing the vortices only slightly changed the turbulent fluxes. Field observations of area-averaged characteristics were conducted in a densely built-up residential neighborhood [97]. Sensible heat fluxes observed at 3.5 times the building height agreed with other measurements. An analysis was presented for a moving flat sheet emerging into a quiescent fluid [98]. Temperature gradients within the sheet were shown to be important to the problem. Heat transfer in a stagnation point flow towards a stretching sheet was described [99]. The effects of elevated freestream turbulence on heat transfer to a gas turbine vane were measured [100]. Correlations in the literature for freestream turbulence augmentation were shown to not be accurate for application to a turbine vane. The effects of leading edge fillets on the turbine vane near the endwall were documented [101]. The fillets were effective in reducing the strength of the horseshoe vortex characteristic of this region. In a similar flow, the effects of non-uniform inlet conditions were measured [102]. Sensitivity of the secondary flow patterns to inlet conditions was documented. Unsteady flow and heat transfer due to passing wakes in a turbine rotor were computed [103]. The method was accurate for subsonic turbine flows. The effects on flow and heat transfer of having a boundary layer fence on the endwall of a 90° turning duct were presented [104]. The flow and heat transfer in the stagnation region of a body in a magnetic field were analyzed [105]. A self-similar solution for describing the viscous dissipation and Ohmic heating effects was presented. The magnetic field tends to delay or prevent flow reversal in the wall-normal direction. Mixing in a vessel was modeled [106]. A unified analysis on enhancing heat transfer with a field synergy principle was presented [107]. It was applied to a finned tube. Performance of pin fins cast into an aluminum coldwall was assessed [108,109]. Experimental measurements were used to document the heat transfer coefficients and the conditions for transition to turbulence. The effects on heat transfer of having perforations on extended surfaces were measured with liquid crystal thermometry [110].

An augmentation of heat transfer on the downstream side of the perforations was documented. The effects of radiation on the problem of flow over a wedge were assessed [111]. The viscosity was allowed to vary. Turbulent mass transport in a circular wall jet was measured [112]. While turbulence intensity increased downstream, the turbulent mass transport declined, indicating a weakening dispersion. The effects of turbulent mixing on the dynamics of a liquid layer accelerated by compressed air were assessed [113]. Cooling of the hot compressed gas adjacent to the liquid was an important part of the process. Flow and heat transfer inside thin films supported by soft seals were studied for flows influenced by external pressure pulsations [114]. Such quantities as the squeezing number, the squeezing frequency, the frequency of pulsations, the fixation number and the thermal squeezing parameter were determined to be controlling parameters. Theoretical solutions were presented for Stokes flow induced by a sliding smooth plate over a finned plate [115]. The change in drag and heat transfer with a change in fin spacing was described with a fin-interaction parameter and a characteristic length scale. The results would be applied to microsystems.

3.3. Compressibility and high-speed flow effects

A computational fluid dynamics (CFD) method was developed to compute the hypersonic flow fields for reenty vehicles [116]. It was shown that the wall surface temperature in the downstream region is significantly elevated by the effects of turbulence due to abalation product gas. A ground testing facility was described for modeling projectile flight heating upon reentry [117]. Analytical and measured results describe transition to turbulence and heating in the turbulent flow. A transformation from the facility results to the actual conditions was proposed. A closed-form simulation of convective heat transfer and heat penetration in spacecraft reenty was proposed [118]. Results were compared against data for the Space Shuttle and the European Atmospheric Reenty Demonstrator. Experiments and computation on crossing-shock-wave/turbulent boundary layer interactions were made with a structure having sharp fins mounted on a flat plate in a Mach 4 flow [119]. Primary features were accurately computed but heat transfer was overpredicted by a factor of 2–2.5.

Mixing with film cooling in supersonic duct flows was computed [120]. Computed temperature differences did not compare well with measured values; however, an integral method was shown to capture the wall temperatures. A coordinated approach using the Navier–Stokes solver and the integral model was proposed.

Boundary layer transition in hypervelocity boundary layers was documented experimentally [121]. The effects of locating a trip on the surface were quantified.

A theory for describing hypersonic blunt-nose shock standoff was presented [122]. It includes non-equilibrium shock-layer chemistry, gas mixing, ionization and dissociation. Numerical simulations were made for non-classical shock wave effects [123]. The method includes Bethe–Zeld'ovich–Thompson fluids, shock "splitting," D'yakov-Kotorovich instability and non-linear heat transfer in strong point explosions.

Predictions were made for laminar hypersonic viscous/inviscid interactions [124]. Benchmark data from an experiment with Mach 9.5 flow over a sharp-tipped double cone were used for validation.

3.4. Analysis and modeling

Laminar-to-turbulent transition for low-Reynolds-number mixed convection in a uniformly heated, vertical tube was modeled [125]. The decay of turbulent kinetic energy in the entry region was documented and the local Grashof number was shown to first increase, then decrease to a fully developed flow value.

Transition and heat transfer predictions in a turbine cascade with different values of free-stream turbulence intensity were simulated with a Reynolds average Navier–Stokes (RANS) model [126]. Emphasis was put on dealing with the insensitivity of the turbulence closure model to free-stream turbulence. A review of advances in large eddy simulation (LES) was presented [127]. This included SubGrid Scale (SGS) modeling, wall modeling and combustion. A non-linear subgrid-scale heat flux model was introduced for turbulent thermal flows [128]. SGS heat flux was computed in terms of a large-scale strain-rate tensor and the temperature gradients. A k-epsilon turbulence closure model was proposed for atmospheric boundary layer computations which include the urban canopy [129]. An improvement was proposed to account for the anisotropy of the turbulence field under density stratification.

A method for simulating unsteady heat transfer by employing eigenmodes extracted from experimental data was presented [130]. It was applied to a case of flow past a heated cylinder.

A heat and mass transfer analogy based on data from a pipe flow was applied to a bubble column [131].

A calculation technique for computing near-surface turbulent fluxes for stably stratified flows was presented [132]. Evidence from climate predictions showed that traditional flux calculation techniques are not sufficiently advanced. The new method accounts for the differences between roughness lengths for momentum and for scalars. The influence of modeling methods on the prediction of local weather was discussed [133]. A two-way coupling of the mesoscale weather prediction model and the land surface hydrologic model were developed. A hydrodynamic model that describes the evolution of vortex structures in the atmosphere was developed [134]. The source of the vortex structures is thermal convection. The model described the amplification of these structures. Justification of a popular model was given for application in pure katabatic (density driven) flow [135]. The model, for eddy diffusivity in atmospheric boundary layer flows, was compared against data. Scalar transport over snow and ice was discussed [136]. Important are wind speed, roughness, temperature, humidity and stratification.

An inverse method was presented for simultaneous estimation of center and surface thermal behavior of a heated cylinder in a cross-flow [137]. No prior information on the functional form of the unknown quantities was needed.

Heat transfer in the transition region to rarefied gas flow was analyzed with Grad's moment method, the Boltzmann equation and a linearized collision term [138]. Important to the problem was describing the boundary condition for the moments. Gas flow over microscale airfoils was numerically simulated using both particle and continuum approaches [139]. The continuum approach was considered to not be suitable for the flow under study due to rarefied effects. Computation of the Chapman–Enskog functions for viscosity and heat transfer in Poiseuille flow was discussed [140]. Direct methods for exact solutions of hydrodynamic and heat and mass transfer equations by the generalized and functional separation of variables were proposed [141]. Some specific examples were considered.

3.5. Unsteady effects

Heat transfer rates to a flowing helium gas with an exponential increase of power input to a heater were measured [142]. An application is a transient in a gas cooled reactor. A non-similar solution and correlation was proposed for heat transfer over a wedge with a sudden change in thermal boundary conditions [143]. Heat transfer during transient compression, including one-dimensional conduction, was modeled and the results were compared with data [144]. It was noted that the development of turbulent heat transport was not properly modeled. The effects of turbulent mixing due to compression of a planar, heated gas layer by a moving liquid layer were experimentally studied [145]. The gas compression by the liquid layer in a deceleration stage was accompanied by the development of a Rayleigh–Taylor instability.

An analysis was presented for a boundary layer control technique in which power to heated strips was selectively supplied [146]. The change to the flow was via the temperature effect on viscosity. The parabolized stability equations (PSE) method was used to document flow stability. Experimental documentation was given for buoyancy-opposed wall jet flow [147]. A plane jet of warm water was injected down one wall of a vertical, rectangular passage into a slowly moving upward stream of cooler water.

The effect of turbulence on Taylor dispersion for oscillatory flows was measured [148]. Shown was that turbulence intensity increases rapidly when the Stokes-layer-based Reynolds number exceeds 535. The ratio of effective diffusivity to the theoretical value for laminar flow was as large as 100 during the turbulent oscillatory flow. A theoretical analysis was presented for laminar pulsating flow [149]. The mechanism by which pulsation affects the developing region was explained. The unsteady compressible boundary layer equation over an impulsively started plate was solved with velocity slip and temperature jump conditions [150]. Added was the conjugate problem where the thermal field in the solid was computed. Unsteady heat transfer in an impulsively started Falkner–Skan flow with constant wall temperature was computed [151]. Results were presented over a range of the Falkner–Skan parameter, m, and Prandtl number.

Simultaneous velocity and surface heat transfer values were measured within an artificially-created turbulent spot in a transitional flow [152]. Particle image velocimetry and thermochromic liquid crystals were used. Predictions of turbine blade heat transfer and aerodynamics were presented using a new boundary layer transition model [153]. Results were compared to experiments.

3.6. Films and interfacial effects

Local and instantaneous distributions of heat transfer rates through wavy films were measured [154]. The Prandtl number dependency was extracted and found to compare well with recently published experimental data. Characteristics of water films falling down flat plates at various inclination angles were measured [155]. Data on mean, minimum and maximum film thicknesses and wave velocities were presented. Characteristics of falling film flow on completely wetted horizontal tubes with gas absorption were measured [156]. Under certain conditions, fine random waves appear in the film. An energy analysis was applied to the problem of stability of an evaporating, thin, falling film in a vertical tube [157]. The mechanism for breakup of the film was described.

3.7. Effects of fluid type or fluid properties

Skin friction and heat transfer rates in power-law fluids on moving surfaces were determined analytically and numerically [158]. The relationships between viscous diffusion and thermal diffusion with changes in the power law parameter n were discussed. Momentum and thermal boundary layer behavior with power-law fluids flowing over a slender cylinder was numerically described [159]. The interplay between shear-thinning, size of the needle and Reynolds number was discussed. Heat transfer from a non-Newtonian fluid to the wall of a stirred tank was experimentally and theoretically examined [160]. A theoretical correlation was developed. Mixed convection of a micropolar fluid along a vertical wavy surface with a discontinuous temperature profile was numerically evaluated [161]. The influences of the micropolar parameters were described. Laminar mixed convection heat transfer from a vertical isothermal cylinder to water with variable physical properties was numerically evaluated [162]. The variations of viscosity, thermal diffusivity and density with temperature are strong.

Thermal slip in oscillatory, rarefied flow was simulated [163]. The Knudsen number was shown to be a more important system parameter than the acoustic Reynolds number. The temperature jump coefficient for flow between two infinite plates was determined using the direct simulation Monte Carlo method [164]. The effect of the Knudsen number was determined by computing the jump with various distances between the two plates. Numerical solutions were used to described rarefaction, compressibility and viscous heating in gas microfilters [165]. Skin friction and form drag were reduced with increases in Knudsen number.

3.8. Flows with reactions

The boundary layer structure under hydrogen combustion with different injection rates was numerically simulated [166]. The presence of a heat-release front delays laminar-turbulent transition from its non-combustion location. The ignition delay of non-premixed stagnation-point flow was numerically evaluated [167]. The effects of flow strain rate, Lewis numbers and Prandtl number on ignition delays were investigated with the model. Non-local turbulent transfer models for turbulent mixing in reacting and non-reacting flows were presented [168]. Results were applied to heat and mass transfer to solid surfaces from turbulent boundary layers.

Non-equilibrium, high-temperature, axisymmetric boundary-layer flows were computed [169]. Wall catalyticity effects were taken into account.

Experimental results and modeling steps were presented for describing the initial growth rate of a cryogenic shear layer under subcritical and superciritcal conditions [170]. The geometry was a liquid nitrogen jet which was injected into a chamber. The behavior changed from a liquid spray-like jet to a gaseous jet as pressure was increased.

4. Channel flows

4.1. Straight-walled ducts

Heat transfer in channel flows begins with a section on the thermal characteristics of flow in straight-wall passages. Friction factors and Nusselt numbers were computed using finite elements for laminar flow in rectangular ducts. Steady slug flow of a Newtonian fluid with constant properties and thermally varying conditions was examined analytically [171]. The laminar-turbulent transition was studied in a fully-developed air flow in a heated horizontal tube [172]. Joule heating and axial heat conduction were studied analytically for a step change in wall temperature in thermally developing flow in a parallel-plate channel [173]. Turbulent flow and heat transfer was computed using mixing length theory in an annular-sectored duct [174]. Four different conditions for laminar flow in a circular tube were defined under thermally developing conditions [175]. A new and continuous approximation is developed for the Nusselt number in hydrodynamically developed flow between parallel plates [176]. A three-dimensional axially parabolic model was used to examine the developing laminar mixed convection in horizontal and vertical tubes; heat and mass transfer were considered [177]. Experiments were conducted of mixed convective heat transfer in horizontal and inclined rectangular channels [178]. Nusselt numbers were predicted for the heat transfer during in-tube cooling of turbulent supercritical carbon dioxide [179]. The k-epsilon model was used to model open channel flows influenced by a magnetic field [180]. The mixed convective heat transfer to air in vertical plane passages was studied experimentally [181]. The Dufour and Soret effects were incorporated in the extended Graetz problem in parallel plate flow [182]. The entrance region of forced laminar flow was investigated while including the emitting and absorbing affects of the gas [183]. The forced flow of gas in circular tubes with intense heating was computed using relatively simply turbulence model; comparisons to experiments were made [184]. Step changes in wall heat flux were studied using direct numerical simulation [185]. The direct numerical simulation of turbulent heat transfer was also carried out in a square duct [186]. Forced convective heat transfer was examined experimentally inside the horizontal tubes of an absorption/compression heat pump [187]. Heat transfer enhancement and local turbulence were considered in the study of lithium annular flow under the influence of a magnetic field [188]. Heat transfer to supercritical carbon dioxide was studied in miniature tubes [189]. The entropy generation in a solid-pipe fluid system was investigated; coolanol, water and mercury were working fluids and copper and steel were considered as pipe material [190]. A horizontal coaxial double-tube hot gas duct was examined [191] and the effect of viscous dissipation on fully-developed laminar mixed convection was studied in a vertical double-passage channel [192]. Finally, one study performed a direct numerical simulation on turbulent channel flow under stable density stratification [193].

4.2. Microchannel heat transfer

Microscale heat transfer was examined in a variety of channel configurations. The three-dimensional flow and heat transfer was computed in heated microchannels [194]. Laminar forced flow in isoflux rectangular microchannels was studied analytically [195]. The impact of microspacing was considered in the slip flow regime between two unsymmetrically placed heated plates [196]. The constant-wall temperature Nusselt number was computed in micro- and nanochannels [197]. A direct Monte Carlo method was used to compute the flow and heat transfer in microchannels with implicit boundary conditions [198]. Monte Carlo methods were also used to simulate the rarified gas flow and heat transfer in microchannels in the Knudsen number range of 0.05–1.0 [199] and of low pressure fluid flow and heat transfer in ducts at high Knudsen numbers [200]. Microchannel heat sinks were studied computationally using water as the working fluid [201]. Nusselt numbers are computed in rectangular microchannels or varying aspect ratio [202]. The thermal performance of microchannel heat sinks was optimized numerically [203]. A combined numerical and experimental study of single-phase microchannel heat sinks was considered [204]. A microheat pipe was fabricated with star grooves and rhombus grooves [205]. A low power microchannel thermal reactor was simulated numerically [206]. Fractal branching was studied as a strategy for cooling of electronic chips using microchannel nets [207]. Experiments were carried out to assess the gaseous flow in microchannels [208]. Heat transfer coefficients were obtained for the supercritical flow of carbon dioxide in horizontal mini/microchannels [209]. An analytical/computational study was discussed on the convection and conduction in a system of slotted microchannels [210]. The thermal-fluid behavior in a small capillary was studied experimentally [211]. The theory of two-phase flow in microchannels with emphasis on the phase change at the meniscus was studied [212].

4.3. Irregular geometries

In this subsection we summarize papers in the literature covering a myriad of geometries, though generally confided to channels. The multichannel narrow-gap fuel element configuration was simulated numerically [213]. A rhombic duct was studied using a Galerkin integral method considering constant wall temperature [214]. The fully-developed flow in an elliptic duct was studied over a range of aspect ratios [215]. The heat transfer characteristics created when a non-premixed flame is introduced into a curved duct was studied experimentally [216]. The endwall heat transfer was investigated in a pin-fin wedge geometry [217]. The heat transfer in a millimeter scale thruster nozzle was studied numerically; good agreement between model and data were observed for non-adiabatic wall conditions [218]. The thermally developing laminar forced convection and heat transfer was studied in corrugated ducts confined by sinusoidal and arc curves [219]; heat transfer rates were also computed through a sinusoidally curved converging–diverging channel [220]. A combined computational and experimental study was undertaken to understand the thermal characteristics in convergent/divergent square ducts [221]. A rectangular cross-section two-pass channel was studied with an inclined divider wall [222]. Two-pass internal coolant passages in a gas turbine were examined experimentally [223]. Heat transfer augmentation in swirling ducts experiencing rolling and pitching was found experimentally [224]. Flow and heat transfer in metal honeycomb was investigated; competing goals of heat transfer and pressure drop were addressed [225]. A multiply-folded, but continuous flow passage was studied numerically; conjugate thermal interaction between the fluid and bounding walls was considered [226]. Laminar forced convection was addressed in branching ducts; effects of branch size were examined [227].

4.4. Finned and profiled ducts

Fins, profiling, protuberances, tape-elements and the like are commonly used to enhance heat transfer or mimic complex geometries used in practice. In this section profiled ducts will be summarized. The convective heat transfer caused by perforated ribs in a turbulent boundary layer was studied experimentally [228]. Reynolds averaged equations were used to investigate the heat transfer changes brought about by ribs in three-dimensional ducts [229]. Turbulent heat transfer was studied experimentally in longitudinal rectangular-fin arrays; different shrouds and geometries were considered [230]. Simulations were undertaken to assess heat transfer augmentation in an intermittently grooved channel [231]. Deep spherical dimples placed on a channel wall were used to augment heat transfer; a computational study was conducted [232]. Longitudinal strip inserts were introduced into a circular tube for laminar flow conditions and for uniform wall heat flux [233]. Twisted tape inserts having different pitch to diameter ratios were examined in turbulent flow [234]. The thermal boundary conditions on the numerical predictions of heat transfer in rib-roughened passages were considered [235]. A numerical simulation was also conducted of turbulent flow in a two-dimensional channel with period slit ribs [236]. Air flowing under laminar conditions was investigated experimentally in a channel having a upper V-corrugated plated heated by radiation [237]. Combined convection and radiation was studied in a tube with circumferential fins and circular disks [238]. The three-dimensional forced laminar convection in ribbed square channels was studied; the study focused on repetitive geometries [239]. An algebraic heat flux model was used to calculate turbulent heat flux in a square duct with one roughened wall [240]. Five different heat transfer surface configurations were studied together with the effect of inlet subcooling on two-phase flow instabilities [241]. The heat transfer caused by discrete rib turbulators was investigated numerically [242]. The entry region of corrugated tubes was studied experimentally using fluids with temperature dependent properties [243]. The affects of aspect ratio, temperature ratio, Reynolds number and flow structure were considered in an experimental study in a dimpled channel [244]. The heat transfer from plates with fins was measured using the naphthalene sublimation technique; microscopic and macroscopic features were compared [245]. Holographic interferometry was used to visualize the unsteady temperature fields in grooved channels with curved vanes [246]. Spectral element methods were used to study the enhanced heat transfer in a flat passage downstream from a grooved channel [247]. Experiments were carried out in a reciprocating duct fitted with 45° crossed ribs [248]. Liquid crystal thermography was used to investigate the forced convective heat transfer in channels with ribs [249]. Experiments were used to assess heat transfer enhancement caused by rectangular blocks at different orientation angles on a surface [250]. The convective heat transfer in ribbed channels experiencing a 180° turn was measured by means of infrared thermography [251]. Fully developed heat transfer was examined in a rectangular duct with surface roughnesses [252].

4.5. Ducts with periodic and unsteady motion

Transient motion, unsteady and periodic flows are considered in this section. Experiments were conducted for various Reynolds numbers and pulsation frequencies to determine the heat transfer characteristics in laminar pipe flow [253]. The unsteady forced convection was investigated in a duct with periodically varying heat generation [254]. An analytical solution was developed for unsteady, conjugated heat transfer in a parallel plate duct [255]. The affect of resonant oscillations on heat transfer in turbulent pipe flow was considered [256]. The temperature distribution is computed analytically to account for viscous dissipation in finite-gap Couette devices [257]. Experiments were conducted to evaluate the heat transfer in a decaying swirl flow [258]. A numerical analysis was undertaken to evaluate the heat transfer from a flat plate, one side of which contains pressurized He II [259]. A combined numerical and experimental study was presented for thermal systems with helically-coiled tubes [260]. The temperature field of a traveling wave was studied in sub-cooled liquid nitrogen [261]. The thermo-acoustic field in a Rijke-tube pulse combustor was verified in a two-dimensional numerical study [262]. Thermally-developing laminar pipe flow was studied for wall and fluid axial conduction [263]. Heat transfer for low-Reynolds number turbulent flow was investigated in a helically dimpled tube [264].

4.6. Multiphase and non-Newtonian flows in channels

Flows consisting of multiple phases, including nanofluids are considered in this section, together with non-Newtonian flows. The flow and heat transfer characteristics of a copper–water nanofluid was studied experimentally [265]. Microencapsulated phase change slurries were studied in circular tubes with constant heat flux [266]. Forced convective heat transfer augmentation was considered for the addition of metallic fibrous materials [267]. Adiabatic air–water experiments were conducted to address the transition regime between churn and annular flow [268]. Heat transfer coefficients were determined for fluid-to-particle continuous flow of suspensions in coiled tube and straight tubes with bends [269]. A LiBr–water absorber was modeled; falling-film and droplet mode heat transfer was addressed [270]. Six different two-phase non-boiling heat transfer correlations were assessed using extensive data sets [271]. Heat transfer measurements were also used to develop correlations for air–water flow in horizontal pipes [272]. Experimental heat transfer coefficients were obtained for a vertical tube positioned at various locations in a circulating fluidized bed [273]. A perturbation-based stoichastic finite element method was used to obtain the heat transfer of a viscoelastic fluid containing elastic spherical particles [274]. Nusselt numbers were predicted for power-law fluids in ducts of various cross-sectional areas; rhombic, isosceles-triangular, elliptical, and semi-elliptical ducts were considered [275]. A Bingham fluid in a thermal entry region was studied using a finite integral transform technique [276]. The effects of power-law rheology, duct eccentricity and thermal boundary conditions were considered in fully-developed laminar flow [277]. Power-law laminar flow was also addressed in a conjugate heat transfer problem in a circular tube [278]. Fully-developed laminar flow of a Phan–Thien–Tanner fluid was examined in pipes and channels with constant wall temperature [279].

5. Separated flows

This section begins with papers addressing heat transfer characteristics in flows experiencing separation, either by rapid changes in geometry (e.g. backward-facing step) or strong adverse pressure gradient. This section will conclude with papers focusing on the thermal-fluids of flow past bluff objects. The flow past a backward-facing step was computed using large-eddy simulation; the heat transfer was examined in detail in the region near reattachment [280]. A computational study addressed energy separation in free shear layers; it was shown that the pressure fluctuations play a major role in the energy separation process [281]. Mixed convection was investigated numerically in vertical ducts with arbitrary cross sections [282]. The three-dimensional forced convection downstream and adjacent to the backward-facing step was computed [283]; mixed convection conditions were also addressed [284]. The effect of step height was incorporated into a study of the three-dimensional flow past the step [285–287]. Heat flux on the floor wall downstream of a step was examined numerically [288]. A large eddy simulation was undertaken of the turbulent flow past a backward-facing step including the influence of property variations [289]. The heat transfer from a diagonal membrane heating surface was considered; the naphthalene sublimation technique was employed [290]. Adiabatic and heating conditions on a laminar airfoil were investigated at moderate subsonic Mach numbers [291]. Correlations of heat transfer coefficients were obtained over blunt-edged flat plates [292]. The heat transfer from a blunt flat plate was also studied in a square channel; three-dimensional simulations are presented [293]. A finite volume computational scheme was used to investigate the natural convection from a heated cylinder in an enclosure [294]. Forced convective heat transfer was also studied over a bank of staggered cylinders [295]. In-line and staggered configurations of wall-mounted cubes was examined experimentally in fully developed turbulent channel flow [296]. One paper addressed heat transfer augmentation caused by the application of a surfactant on the surface of horizontal tube bundles [297]. Large eddy simulation provided insight into the turbulent flow from a multi-layered wall-mounted cube matrix [298]. A three-dimensional numerical model was developed to assess the heat transfer in a ceramic oxygen generator [299]. Mach 5 flow over a hemisphere was studied to examine magnetic flow control and the corresponding heat transfer [300]. The forced convection in a channel with a built-in triangular prism was computed [301]. Mixed convection was investigated from elliptic tubes are various angles of attack to a fluctuating free stream [302]. Computations were used to determine the heat transfer from a heated oscillating cylinder in cross flow [303]. The heat transfer in a supersonic dusty-gas flow past a blunt body was considered at moderate and high Reynolds numbers [304]. The mechanism responsible for heat transfer augmentation through the spanwise and longitudinal vortices is addressed in a study of the turbulent wake of a square cylinder near a wall [305]. The laminar convective heat transfer was measured to a blunt cone at Mach 5.75 [306]. A numerical study was conducted of channel flow past a bluff body; the channel was differentially heated and had a built-in triangular prism [307]. Turbulent unsteady flow in a channel was investigated numerically; periodically placed square bars were arranged side-by-side to the approaching flow [308]. The enhancement in heat transfer rate caused by acoustic streaming is studied using ultrasonic flexural vibrations [309]. Acoustic streaming was also studied in the context of a cylindrical resonator [310]. Turbulent statistics and heat transfer are addressed in a study using large eddy simulation in a stratified shear flow [311]. The effects of a catalytic surface reaction on convective heat transfer from a heated cylinder is presented [312]. The mixed convection from a heated horizontal cylinder is analyzed; focus is placed on thermal instabilities [313]. The performance of an enthalpy exchanger is placed in the context of the effectiveness-NTU method; experiments are presented which incorporate a novel hydrophilic membrane core [314]. The impact of free-falling waves in turbulent films on the associated heat transfer rates is explored [315]. The thermal law of the wall was studied for separating and recirculating flows [316].

6. Heat transfer in porous media

The literature on heat and mass transfer in porous media continues to expand, and several studies of a very fundamental nature capture the breadth of recent activity.

A general formulation of the governing equations was developed to describe thermo-mechanical effects of a weakly viscous flow in a porous medium, including the Dufour, Sort and virtual mass effects [317]. The lattice Boltzmann model for isothermal incompressible flow was developed taking into account the porosity in the equilibrium distribution and adding a force term to the evolution equation to account for drag forces [318].

The constant heat flux boundary condition was analyzed in the absence of local thermal equilibrium and for the effects of all pertinent hydrodynamic and structural parameters [319,320]. Thermal non-equilibrium via the two-equation approach was considered for a structured medium [321]. The effects of Darcy, Prandtl, and Reynolds numbers on local thermal equilibrium when convection is the dominant mode of heat transport was quantified via an order of magnitude analysis [322].

A two-equation model was developed for convective heat transfer including the effects of inertia and the solid boundary on the Nusselt number [323]. The method of multi-scale asymptotic expansions was used to demonstrate how flow in a porous medium can be equivalently represented by an equivalent macroscopic system [324]. Inhomogeneity and anisotropy in the porous material and their effects on forced and free convection were investigated both numerically and analytically [325–327].

Multiphase phase flow analysis based on molecular populations for each phase was used to develop macroscale balances [328]. Foaming flow under rapid depressurization and no bubble recombination was modeled based on velocity via Darcy's Law, pressure and dispersed gas fraction [329]. Dispersion of a solute in two-phase flow was modeled via reconstruction of the porous medium, the immiscible lattice Boltzmann model, and random walks [330].

6.1. Property determination

The stagnant effective thermal conductivity of a bed of spheres was determined via multi-particle simulation by modeling two-particle interactions, and predicted results shows good agreement with experiments without introducing new adjustable parameters [331]. More traditional microstructural models involving a known particle contact area and a significant fraction of fluid phase heat transfer was shown to give good agreement with experiments [332,333]. Measurements of axial conductivity in a packed bed were reported for a range of fluid/solid conductivity ratios [334], as was an analysis of axial thermal dispersion of open cellular porous materials [335]. The contribution of thermal radiation to the overall thermal conductivity of a porous medium was determined via a model comprising either spheres or cylinders [336] and an experiment in which boundary heating was used to validate the calculated emissivity [337].

The apparent permeability of a porous layer was found to be significantly lower than its intrinsic permeability when the layer is sufficiently thin [338]. Wave propagation in a linear elastic fluid-saturated porous medium was found to be essentially adiabatic even when convection through large pores is taken into account [339].

As an extension of a particulate porous medium, metal foams have begun to receive some attention. Two comprehensive articles summarizing their properties and outlining applications have appeared [340,341].

6.2. External flow and heat transfer

Free and mixed convection on vertical surfaces under various thermal boundary conditions and external flow conditions remain problems of focus both experimentally and analytically. Similarity, non-similarity and integral solutions for the vertical plate produced heat transfer coefficients as a function of wall heating conditions, stratification, and volumetric heating in the porous medium [342–344]. Free convection from a vertical wavy surface was measured via the mass transfer analogy for a range of particles sizes and surface amplitude-to-wavelength ratios [345]. Existence criteria for self-similar solutions for the permeable surface with an inverse linear temperature profile were developed, and bounds on the minimum suction rates were established [346]. Heat transfer in non-Newtonian fluids from two-dimensional and axisymmetric permeable bodies of arbitrary shape was computed via the local non-similarity method, and results were presented in terms of fluid properties and the wall boundary condition [347]. Aiding and opposing mixed convection from a cylinder in a saturated medium was computed, and oscillatory flow observed for high Reynolds number [348]. Wall mass flux effects in mixed convection on an inclined surface showed that the heat transfer rate increases with suction [349].

Analysis of inertia effects on the two-dimensional stability of natural convection over horizontal and inclined plates showed that increased Forcheimer number increases the heat transfer rates with the flow more stable to vortex modes of instability [350]. Wall conductivity effects on free convection from a vertical plate were analyzed for the case of one-dimensional conduction, and results compare favorably with more computationally demanding methods [351].

An analysis of conductive to convective transport from a flat plate to a saturated porous medium showed that the transition from transient heat conduction to steady forced convection is independent of the wall thermal boundary condition and the presence of thermal dispersion [352]. Nusselt numbers in forced convection past a parabolic cylinder embedded in a porous medium were shown to decrease with Darcy number but increase with inertia effects [353]. An analysis of forced convection heat transfer from stretching boundary for a visco-elastic fluid showed the connection between the viscoelastic and inertia parameters [354,355].

Random and structured porosity models were used in simulating forced convection through a porous block situated in a channel, and criteria for enhancing heat transfer were proposed [356]. Transient solutions for heat transfer in a semitransparent porous medium in channel flow were reported for a range of flow and thermal radiation parameters [357].

Magnetic field effects on natural convection over a permeable conical surface embedded in a heat-generating porous medium were computed for a range of magnetic and wall blowing parameters [358]. A similar study considered a power-law fluid and non-Darcy effects [359]. Hydromagnetic forced convection was analyzed for a non-Newtonian fluid with a volumetric heat source over an accelerating surface and a set of non-dimensional parameters for transport of heat and mass were obtained [360].

6.3. Packed beds

Forced and mixed convection in packed beds and porous channels have been the focus of a variety of numerical studies and modeling efforts. As in recent years, the influences of wall effects [361], anisotropy [362], viscous dissipation [363] and dispersion [364] on transport of heat and mass have been focal points but with little comparison to experiment. Structured media, such as that produced by staggered parallel fiber arrays for filtering, were similarly treated numerically with bulk and Brownian transport of suspended particles [365]. Flow and heat transfer in hydrothermal systems with discrete cracks were show to depend on Peclet number, permeability, and presence of cracks [366]. Mixed convection in vertical channel flow was analyzed in terms of permeability variations under the assumption of negligible Brinkman and Forcheimer effects [367]. Aiding mixed convection in an anisotropic channel with oblique principal axes was analyzed for the full range of possible flows to elucidate effects of permeability variations [368].

Measurements of interstitial convective heat transfer and frictional drag for duct flow through metal foams showed that friction factor and volumetric heat transfer coefficient increase with lower foam porosity at a fixed Reynolds number [369]. Forced convection in channels filled with metallic fibers was numerically analyzed and found to be influenced by stagnant thermal conductivity, Darcy number and fiber thickness [370].

Research was reported on the validity of the thermal equilibrium assumption [321]. Laminar forced convection in structured porous media, including combined free and porous zone flows, revealed some interesting flow patterns and possible existence of recirculating flow [371–373]. Measurements of heat transfer to a packed bed comprising mono-sized glass spheres and either water or a water–glycerin solution were interpreted in terms measured temperature profiles [374]. For three-dimensional flow, a combined time and space discretization method was developed [375].

Fluidized bed flow and heat transfer were investigated experimentally for both two- and three-phase beds. Heat transfer measurements from a heated vibrating cylinder in a bed of glass particles displayed different regimes depending on bed operating parameters [376]. Experiments on heat transfer to wall surfaces and to a variety of immersed bodies were correlated for wide range of Archimedes number under slugging flow [377]. In other experiments, bubble and slug lengths were determined by decomposition of non-invasive power spectral density measurements [378]. The addition of angled deflectors to the fin region of a membrane water–wall heat exchanger surface in a circulating fluidized bed was shown to produce a significant increase in heat transfer rates [379].

Experiments on two- and three-phase fluidized beds showed that heat transfer coefficients exhibit a maximum depending on gas and liquid velocities [380]. Heat transfer coefficients to large spheres in a fluidized sand bed were measured for a range of gas velocities and interpreted with a model that does not depend on bubble fraction [381]. Analysis of high temperature circulating fluidized beds showed that thermal radiation can account for up to sixty percent of total heat transfer rate, depending on particle and gas convection rates [382]. For the particulate fluid beds, analysis showed that the heat transfer coefficient increases to a maximum and then decreases as bed void fraction increases [383].

6.4. Porous layers and enclosures

The onset of thermal convection in layers heated from below was analyzed to determine the influences of a magnetic field, gravity variation, rotation, internal heat sources, thermal radiation, and vertical through flow [384–386]. Heat transfer characteristics at the onset of chaos in bottom-heated cavities were obtained via a generalized integral transform technique [387]. The onset of convection in Darcy–Brinkman flow was determined via an asymptotic analysis of the singular perturbation problem in the limit of small Darcy number [388]. A two-temperature model was also employed for the same flow model to show that thermal non-equilibrium can raise the critical Rayleigh number above Lapwood's value [389].

A two-equation model including viscous and inertial effects was used to determine non-equilibrium effects on overall Nusselt numbers for natural convection in a square enclosure [390,391]. A non-equilibrium model was shown to better represent non-Darcy natural convection in high porosity metal foams heated from below than one in which local thermal equilibrium is assumed [392].

Numerical solutions for transient three-dimensional Darcy natural convection in vertical cavities were obtained to show the succession of stable solutions [393]. Non-Darcy effects were similarly analyzed for the vertical annulus, and heat transfer rate decreased with decreased Darcy number [394]. For the spherical annular sector, natural convection exhibits multi-cellular flows for small aspect ratio [395]. Convection in a tilted fracture in an otherwise impermeable domain was analyzed to predict the effects of convection on the overall temperature distribution [396].

Natural convection in a vertical cavity comprising two layers of different permeability was shown to exhibit a wide range of penetrative flows depending on Rayleigh number and the permeability ratio [397]. Transient convection with heat generation was numerically analyzed for two-dimensional flow in a rectangular cavity with air as the fluid phase [398]. A parallel study for a cylindrical cavity revealed the effects of aspect ratio and anisotropy on heat transfer coefficients [399].

For cavities with an oscillating lid, permeability has a significant effect on flow structure and a resonant frequency was noted for a particular Darcy number [400]. Flow and heat transfer in a partially filled rectangular cavity with heating from the sides shows the existence of a quasi-parallel solution with a linear vertical temperature distribution [401]. Natural convection in a superposed fluid and porous layer shows that the Marangoni effect enhances flow in the fluid layer, which results in a reduction of buoyancy driven convection in the porous sub-layer [402]. Mixed convective effects were numerically analyzed for two-dimensional cavities to obtain flow structure and overall heat transfer rates [403,404].

Double diffusive convection in an anisotropic medium with opposing buoyancy temperature and solute gradients found to exhibit multiple solutions and oscillating flow [405]. Oscillatory solutions were also found for the case heat and mass fluxes were opposed [406,407]. Doubly diffusive non-Darcian flow driven by the upper surface exhibited the effects of varying Lewis and Richardson numbers [408]. Double diffusive natural convection in a stratified square cavity was found to be markedly affected by unequal species and thermal diffusion coefficients [409]. Double diffusive convection driven by cross gradients in a stably stratified enclosure showed little difference in heat and mast transfer rates between the two- and three-dimensional numerical solutions [410]. A numerical solution was reported for double diffusive convection with parallel transverse temperature and concentration gradients in the presence of heat generation or absorption [411,412].

Combined conduction, convection and thermal radiation in a semi-transparent porous sphere were computed via a modified discrete ordinate method [413].

6.5. Coupled heat and mass transfer

Theoretical work was reported on an unconditionally stable numerical method for the general case where material properties vary with moisture content [414] and on the kinetics of moisture and heat transfer in capillary media and in aerosols [415]. A conjugate gradient inverse method was developed to determine unknown time-dependent Biot numbers and transport based on interior measurements of temperature and moisture [416], and a multi-level time scheme was developed for numerically solving the non-linear Luikov system [417].

A review of several pore-network models for computing effective transport properties and transport rates in capillary media has identified several open problems for further research [418]. An analytic solution based on a quasi-steady approach results in a constant speed for the drying front, which is corroborated by experiments [419]. Luikov's equations for capillary media were solved with the aid of measured temperature and moisture content [420] for both the direct and inverse problems [421]. A film flow model was developed based on a network of capillary porous tubes for free water flow prior to the onset of the hygroscopic regime [422]. A more general numerical study of multistage drying regimes determined that total drying time is mainly dependent on the relative humidity of the drying medium [423]. A novel heater was developed and characterized for rapid vaporization of sub-cooled liquid in a capillary medium [424].

Vacuum drying in randomly packed particles was measured at constant heat input to qualitatively determine internal controlling factors on drying rates [425]. Microwave drying of capillary media was similarly investigated to determine the influence of irradiation time, particle size, and initial moisture content on internal temperature and moisture distributions [426,427]. Drying of bed particles and immersed samples in fluidized beds was investigated via experiments and semi-empirical modeling [428–430]. Temperature, moisture content, and pore pressure were measured for the drying of concrete to determine the rate of vapor penetration [431], and mass diffusivity was determined based on non-stationary moisture absorption measurements [432,433].

Packed bed combustion of coke particles was investigated experimentally and data are reported for temperature, gas concentration, particle size and sphericity, and void fractions [434]. A coupled internal-external gas-phase model of the combustion of a porous carbon particle in oxygen was developed to predict the formation of CO and CO_2 [435]. An experimental parameter study of solid waste incineration on a full-scale moving bed produced rich data set that includes internal NO_x profiles [436]. Forced-flow smoldering in flat polyurethane foams was simulated in wind tunnel tests to determine the coupling between the external boundary layer and front propagation [437]. Data on flame temperature, location of the vapor–liquid interface, vapor region propagation, and fuel residue distribution in non-spread diffusion flames of liquid soaked porous beds were reported and compared to predictions of a Stefan-type model [438]. Experiments on combustion in media show that there are critical conditions for the initiation and extinction of super-adiabatic combustion in steady flow [439]. A numerical model of planar premixed methane flames in ceramic media suggest that heat transfer between phases remains decoupled from the initial flame chemistry [440].

The role of adsorption and phase change in the characterization of low moisture materials was modeled with the phase change rate related to local non-equilibrium through a delay coefficient [441]. An improved variable switching scheme for multi-phase transport in soils with a non-aqueous liquid phase developed [442]. Related studies considered similar processes for large scale geologic systems, including fracture flow and imbibition effects [443–446]. Mineralization and ore body formation in hydrothermal/sedimentary basins was successfully modeled in terms of the pore-fluid velocity and the equilibrium concentration [447,448].

Optimal sublimation rates in a porous half-space were determined in terms of the vapor mass concentration at the sublimation front [449]. Direct contact melting of ice particles was found to exhibit distinct regimes for very small and large particle diameter [450]. Convective melting of a granular bed under microgravity was experimentally investigated and successfully decoupled buoyancy effects due to density differences [451]. Preferential flow paths formed during the dissolution of a porous medium were found to depend on the properties of the medium at the pore scale [452]. Heat transfer with phase change in an inclined packed enclosure was numerically determined, and a Nusselt-versus-Rayleigh–Darcy number was developed [453].

Moisture transport in paperboard was modeled in terms of a linear driving force transport at the interface of a system of continuous hygroscopic fibers and voids and found dependent on relative values of diffusion and adsorption parameters [454]. Convective heat and moisture transport coefficients in cotton material were measured and modeled in terms of the speed of air penetrating the material [455,456], and a companion study considered periodic air flow, such as occurs in walking [457]. Fabric thickness and porosity were shown to significantly affect moisture transfer via a model that incorporates liquid diffusion in the mass and energy conservation equations [458]. Related studies incorporate evaporation and mobile condensates in fibrous insulation and building systems [459–461]. Moisture content and effects of non-uniformity in percolation were investigated with respect to drying of potatoes [462].

7. Experimental methods

7.1. Introduction

The need for measurements in heat transfer and related flow studies remains strong. This is particularly true in situations which cannot be completely defined in fairly straightforward numerical modeling. This includes, among other things, two phase flow, and many turbulent flow situations. Modeling of the turbulent heat transport process is still not refined to the point of making accurate predictions in particular in flows that have not been well studied and well measured. Thus, if nothing else, the measurements must be used to refine turbulence models and to some extent numerical methods. In addition flow and thermal measurement are required in many industrial and, for that matter, consumer-used systems. Accurate and reliable data are required, which gives rise to the need for good methods of measuring temperature, heat transfer and velocity, and also other flow parameters, as well as property measurements of real materials.

7.2. Heat transfer

Visualization techniques have been used in a number of heat transfer measurements. This can mean an application of a thermochromic liquid crystal (TLC) and a transient experiment in which the change in local temperature on a surface with time, deduced from the local color changes of the TLC, are used to calculate the local heat flux. Such a system has been applied in a supersonic blowdown tunnel for Mach-three flow over a surface [463]. An uncertainty analysis [464] shows the potential error, when obtaining local heat transfer coefficients, from discrete random uncertainties in TLC measured temperatures. Luminescent coatings are used [465] to measure surface heat transfer rates in a short-duration hypersonic flow at Mach numbers between 9.5 and 11.1. A new simplified model [466] can be used for data reduction of transient heat transfer measurements in internal channel heating and cooling investigations. A two dimensional transient heat conduction analysis [467] improves the reliability of heat transfer measurements for erodable ribbon-element heat flux gauges used in internal combustion engines. A design analysis [468] of a heat flux sensor based on the transverse Seebeck effect demonstrates how measurements of instantaneous values of heat flux can be obtained in a free convection boundary layer. The operating principles and calibration procedure for a new-design differential calorimeter used for heat transfer measurement have been described [469].

7.3. Temperature measurement

A telocentric objective lens used with a digital camera eliminates the angular dependence in the color determination which is critical in use of thermochromic liquid crystals for precision measurements [470]. An interfacial temperature sensor of 1 μm thickness, developed using microfabrication techniques, has measured temperatures in a simulated rapid solidification process [471]. Fluorescence properties of a special thermographic phosphor permit high spatial- and temporal-resolution temperature measurement [472]. Black-body optical-fiber thermometers with a metallic coated sensing tip are used for measurements in high temperature environments [473]. Numerical experiments [474] evaluate the use of a passive acoustic thermal tomograph for providing spatial resolution of temperature on a surface. An infrared-charge-coupled device (ccd) camera provides the temperature distribution at the cutting edge of a machine tool [475].

7.4. Velocity measurement

A closely-spaced array of hot-film sensors is used [476] to determine the skin friction distribution on a circular cylinder. A thermal tuft of cool air near a specially coated TLC surface can indicate very low velocities in weakly separated flows [477]. A refined analysis [478] improves a speckled tomography technique to reconstruct both large-scale structure and microstructure in turbulent flows. Flow patterns can be deduced using process tomography [479]. A cross correlation technique [480] improves the time resolution of ultrasonic velocity measurements in turbulent flows. A numerical analysis for the two dimensional heat transfer from a circular cylinder in Couette flow [481] indicates the correction needed for hot wire measurements near a wall.

7.5. Miscellaneous

Pattern recognition analysis applied to a rake of resistive probes [482] indicates the presence of bubble clusters in turbulent bubbly flow. An X-ray tube and scintillation counters can measure the void fraction in flows of an air–water mixture [483]. Two phase gas liquid flows have been studied [484] with an extraction device in which the air and liquid flows are measured separately. A wire mesh sensor used with a newly developed algorithm for special field reconstruction [485] provides local instantaneous true gas velocities in a bubble flow. Surface reflectance measurements in the far infrared are used to determine condensate film thickness on a surface [486]. A special pressure-sensitive paint is used [487] in a cryogenic steady flow wind tunnel for pressure measurements. Silicon-based thermal conductivity detectors have been used in a number of geometries [488]. A three dimensional finite model [489] predicts the thermal response of calorimeters used to measure pulsed laser energies. Calibration methods have been applied [490] to temperature-modulated differential scanning calorimeters.

8. Natural convection-internal flows

8.1. Highlights

Natural convection in a square or rectangular cavity continues to receive considerable interest. Most investigations are numerical in nature and address issues such as localized heating or cooling, partial obstructions, variable fluid properties and internal heat generation. A two-phase fluid containing shape memory alloy/rubber membrane particles has been proposed that will increase in bulk density as the temperature increases creating a negatively buoyant fluid.

8.2. Fundamental studies

Analysis of symmetries and self-similar forms of the Navier–Stokes and Fourier–Kirchhoff equations was used to reduce the order of equations and obtain analytical solutions to a number of natural convection problems [491]. A review of similitude criteria applied to natural convection was given [492]. Measurements were made in large aspect ratio horizontal layers for Ra from 10^7 to 10^9 that support the logarithmic variation for velocity and temperature profiles in the layer [493]. The validity of the incompressible flow model coupled with the Boussinesq approximation that is widely used in natural convection studies was discussed [494]. Stability and chaotic characteristics of a vertical wall plume were studied that showed the flow can be classified into four regions [495] (Ishida). An interesting inverse buoyant fluid was described in which particles composed of shape memory alloy and rubber bellows make the bulk fluid negatively buoyant when heated [496].

8.3. Internal heat generation

Stability and bifurcation were studied numerically for steady internal heating of a horizontal layer cooled from above and below [497] and for a vertical channel [498]. Three-dimensional numerical solutions were obtained for liquid metal contained in a cubic enclosure heated in a uniform magnetic field [499]. Oscillating sidewall temperature on a cavity containing an internally heated fluid was able to set up resonance at specific oscillation frequencies [500]. Studies of internal heating were also applied to geoplanetary flows [501–505].

8.4. Thermocapillary flows

A similarity solution was obtained for developing Marangoni flow over a flat surface [506]. Approximate similarity of temperature and velocity profiles was found for large Prandtl number in a floating zone technique used for crystal production [507]. Thermocapillary flows were studied in various containers including rectangular cavities [508,509] and a liquid bridge [510]. Effects of Marangoni type flows were studied for bubbles, drops or particles in suspension [511] and for single glycerine drops [512]. Heat transfer was found to be enhanced by thermocapillary flows in an ammonia–water absorption process by adding *n*-octanol [513].

8.5. Enclosures

Scaling of heat transfer in large Prandtl number fluids [514] and experimental data obtained using high pressure gases [515] were given for large Rayleigh number flows in horizontal layers. Effects of time dependent gravity on the thermal stability of a fluid layer was given [516]. Rayleigh-Benard type problems were investigated for square [517] and cubical [518] cavities, truncated cylinders [519], a deep cavity [520] and a layer with an inclined upper surface [521]. The horizontal layer geometry was also used to study combined heat and mass transfer [522] and a layer containing two immiscible fluids [523].

Numerical solutions were obtained for natural convection in square cavities to illustrate numerical methods [524,525] and to study the effects of magnetic fields, temperature dependent fluids and pseudoplastic fluids [526–528]. The flow of a magnetic fluid in a square Hele–Shaw cell was observed using a shadowgraph method [529]. Numerical solutions were obtained for natural convection in rectangular cavities to investigate combined heat and mass transfer [530,531], magnetic damping of the flow of a low-conducting aqueous solution [532] and temperature variation of the uninsulated upper wall [533]. Variations of rectangular enclosure geometry include an inclined enclosure heated from below [534], an inclined enclosure with a wavy lower wall [535] and a vertical enclosure with two opposing wavy walls [536]. Solutions for cubical cavities were presented that incorporate various effects of a magnetic field [534,537,538]. A comparison of ten numerical solutions to benchmark experimental data on natural convection in a tilted cubical enclosure containing air was presented [539]. Localized thermal sources and sinks in rectangular cavities have been investigated numerically [524,540–542]. Several studies of partial internal partitions in rectangular enclosures have been made [543–548]. Vertical [549] and inclined [550] open cavities have been studied numerically. Resonance inside a rectangular cavity heated from the side with an oscillating moving bottom wall was studied experimentally using air [551]. Additional geometries considered include a semi-cylindrical cavity [552], an inclined arc-shaped enclosure [553], a dome [554] and a spent fuel cask [555].

8.6. Vertical cylinders, ducts and annuli

Heat transfer in a vertical cylinder was studied for the case of conducting walls [556], the effects of a strong magnetic field on air [557,558] and in an annulus heated from below [559]. Natural convection was studied for a vertical duct with triangular, circular, square, and rectangular cross sections [560]. Measurements of velocity were made in turbulent flow contained within symmetrically and unsymmetrically heated vertical channels [561]. The effect of partial obstructions in a vertical channel was modeled for perfectly conducting or adiabatic obstructions located near the entrance, exit or in the center of the channel [562].

8.7. Spherical and horizontal cylindrical annuli

The stability of flow in a spherical annulus was investigated using a Galerkin–Chebychev spectral method for axisymmetric disturbances for a wide range in Prandtl number and aspect ratio [563]. Real-time holographic interferometry was used to study convection in a spherical annulus when both thermal and electric field driving forces are present [564]. Numerical methods were used to solve the natural convection flow in horizontal eccentric cylindrical annuli [565–567]. Three-dimensional flow was studied in a horizontal concentric annulus with open ends [568]. Numerical methods were used to study the effects of aspect ratio and eccentricity on the heat transfer from an isothermal horizontal cylinder to its square enclosure [569].

8.8. Mixed convection

Experimental [570] and numerical [571] approaches have been used to investigate the flow patterns in horizontal ducts heated from below. Flow reversal of cold fluid flowing downward in a vertical rectangular duct has been studied when the walls are given a constant heat flux boundary condition [572]. Experiments were performed using air and water to study the influence of variable properties on natural convection in a vertical annulus [573,574]. Transient spin up of the contents of a vertical cylindrical container with the bottom heated showed differential spin up rates depending on the temperature of the fluid [575]. Various air return locations were investigated to determine their performance on the displacement ventilation airflow pattern in a room [576]. Other studies of mixed convection include falling films [577], open enclosures [578], a square cavity with an internal protrusion [579] and an inclined ice melting layer [580].

8.9. Fires

Numerical solutions were presented for several relevant problems including ventilation and fire spread in highway tunnels [581]. A three-dimensional forest fire model was described that included drying, pyrolysis and combustion of the emitted gases [582]. Additional modeling has been conducted for the incineration of solid waste on a moving bed [583] and a one-dimensional model for pyrolysis of charring materials [584]. Experiments were performed to study the effect of a red phosphorous flame retardant [585].

8.10. Miscellaneous

Double diffusive convection [586,587] and thermal convection in near-critical fluids [588] were studied under microgravity conditions. Double diffusive flow structures were visualized by injecting glycerine into the bottom of a water layer [589]. Numerical methods for simulating aerosol growth and transport in natural convection fields were summarized [590]. Air flows in heated attic spaces were simulated numerically including the installation of ceiling fans to mix the stratified flow [591]. A mathematical model was developed for the reduction of magnesium in a vertical retort [592].

9. Natural convection-external flows

9.1. Vertical plate

The isolated semi-infinite vertical flat plate continues to be addressed with variations in thermal boundary conditions, properties of the surrounding fluid and surface mass transfer. The full Navier–Stokes equations were solved for a plate with constant, uniform heat flux [593] and experiments were performed in air using transient Joule heating of a thin graphite foil [594]. A uniform surface heat flux was also used in a study of a plate immersed into a chemically reacting system [595] and a plate subject to periodic heat flux in the form of a step function [596]. Combined heat and mass transfer rates were measured during frost formation [597] and predicted in a viscous dissipative fluid [598]. Heat transfer from an isothermal plate to glycerol with variable thermophysical properties was predicted numerically [599] as was heat transfer to water including the effects of surface blowing or suction [600]. Direct numerical simulation was used to study unsteady natural convection from an impulsively heated plate immersed in a linearly stratified fluid [601]. Another study added the effects of a permeable surface and magnetic field heat absorption effects [602].

9.2. Horizontal and inclined plates

Closed form solutions were presented for heat transfer below an isothermal horizontal flat strip [603]. A numerical study was performed for natural convection above a uniformly heated flat plate in a micropolar fluid [604]. Heat transfer from a horizontal flat plate was found to increase by a factor of three when a corona wind was applied using a single steel wire bounded by two copper wires [605]. A heated inclined plate immersed in a water tank was used to study the effect of spanwise arrays of heating elements [606]. Time invariant spanwise-periodic heating was found to generate counter rotating vortex pairs that resulted in increased heat transfer and fluid flow rate. A numerical study of a uniformly heated plate showed that the heat transfer was complex when the angle of inclination was less than 10° but that the results for angles larger than 10 degrees could be correlated very well [607]. An impirical heat transfer correlation was also developed for inclined isothermal circular disks [608].

9.3. Channels

Turbulent free convection in a vertical open channel was investigated [609] to determine the effects of specific volume variation in weakly compressible flows. The effects of a constant heat source at the centerline [610] and a central isothermal or insulated plate [611] in a vertical open channel were studied numerically. Experiments were performed on an inclined channel with three heated strips mounted on the upper wall [612]. For inclinations less than 85°, the channel spacing was not important whereas it was for larger angles.

9.4. Cylinders and cones

Natural convection about a horizontal cylinder in air was studied using holographic interferometry [613]. A theoretical study was performed to determine whether or not homogeneous nucleation of salt is possible in the natural convection boundary layer of a cylinder immersed into a salt solution [614]. It was shown that the Lewis number is the critical property in determining whether homogeneous nucleation is possible. An electrochemical mass transfer technique was used to measure the mass transfer coefficients from upward [615] and downward facing [616] truncated cones. Governing non-similarity boundary layer equations were solved to determine natural convection from a vertical circular cone with either uniform surface temperature or constant surface heat flux [617].

9.5. Plumes

A numerical study was performed to investigate the effect of uniform or parabolic nozzle temperature and velocity exit conditions on vertical buoyant jet flow [618]. A correlation to predict the virtual origin of a thermal plume was presented. Two turbulence models were compared using a buoyant diffusion flame [619]. A modified version of Hanjalic's model was found to give better agreement with experimental data than the low-Reynolds number k-epsilon model of Ince and Launder. A streamline-upwind/Petrov–Galerkin finite element method was developed for buoyancy-driven incompressible flows and applied to atmospheric buoyant plumes [620]. A heat generating, salt containing plume in a sloping fresh water aquifer was studied to simulate deep-well disposal of radioactive waste [621].

9.6. Mixed convection

Similarity and local similarity solutions were obtained for the boundary layer equations representing a moving permeable vertical surface with aiding or opposing flow [622]. Numerical solutions were presented for stagnation flow on a vertical heated plate after both the free stream velocity and heat flux are suddenly increased [623]. Steady heat transfer from a vertical wavy plate in a non-Newtonian fluid [624] and thermal instability over horizontal and inclined surfaces [625] were studied theoretically. A study of heat sink fin arrays [626] showed that the pin fin configuration generally outperforms other geometries. Two experimental studies were performed on water and ethylene glycol in horizontal dimpled tubes [627] and air in a horizontal channel with the bottom and side walls heated and the top cooled [628]. Mixed convection in horizontal [629,630] and vertical [631] channels were solved numerically when discrete heating elements were present. A combined experimental and numerical study was performed to investigate the effect of heat on the stability of a horizontal vortex street [632]. Natural and mixed convection were studied for mass transfer from droplets [633] and from a sphere that represents a hot film anemometer probe [634]. Experiments were performed to study aiding and opposing mixed convection flow from a sphere for low values of Grashof and Reynolds numbers [635]. Heat transfer was found to be significantly enhanced when a sphere oscillates vertically in forced convection but the enhancement decays when the Grashof number becomes significant [636].

10. Convection from rotating surfaces

10.1. Rotating discs

Flow and heat transfer to rotating discs was numerically solved with a focus on the transition between two-dimensional and axisymmetric flows [637]. Flow characteristics when natural convection is the dominating heat transfer mode were measured and reveal the behavior of circumferential vortices and fluctuating velocity and temperature [638]. Analysis of droplet formation via the breakup of a liquid surface films was also reported [639].

Impingement laminar heat transfer was calculated via the integral method, and good agreement with existing experiments was obtained [640]. For laminar planer flow over a rotating disc, Nusselt number correlations have been calculated and applied to disc brake cooling [641]. Wind tunnel experiments were employed to determine effects of wall rotation for turbulent and transitional flows with wall heating [642,643]. Transient heat transfer for hydromagnetic spin up and spin down of a vertical disc was calculated under the influence of a strong buoyancy force due to wall heating [644].

10.2. Rotating channels

Turbulence modeling in rotating channel flows encompassed direct numerical simulation, k-epsilon, large-eddy simulation, and explicit algebraic Reynolds stress methods. Flow structures, wall shear stress, effects of buoyancy and the overall heat balance were variously computed and in some cases, comparisons with measurements revealed good agreement [645–649]. The case of generated swirl in circular ducts was also treated via a turbulence modeling [650]. Calculations of fully developed turbulent flows in orthogonally rotating and stationary curved ducts were compared and a set of dimensionless parameters revealed a degree of similarity between them [651]. Turbulence modulation by dispersed solid particles was also reported via direction numerical simulation [652]. The limit of very flat ducts represented by rotating parallel planes was investigated numerically for a range of flow regimes, including very low Knudsen number [653].

Measurements via the PIV method obtained average turbulent kinetic energy, secondary flow structure, and mean velocity distribution in a two-pass square channel with ribbed walls [654]. Measurements in a flat rectangular duct with constant wall heat flux provided insight into the effects of Coriolis forces in the absence of buoyancy [655].

Developing laminar flow for an incompressible, constant viscosity fluid in a smooth duct with a 180° bend was calculated, and the degree to which rotation affects the secondary flows was compared to the no-rotation case [656]. Flow and heat transfer in ribbed channels were computed to determine the degree of heat transfer enhancement, and results indicate an optimal rib angle depending on flow conditions, channel aspect ration, and rotation parameters [657–660]. The special case of flat ducts with pin-fins was investigated experimentally with constant wall heat flux, and a variation of heat transfer coefficient with transverse location was discovered [661].

10.3. Enclosures

Analysis of laminar compressible and incompressible flow and heat transfer in the rotating annulus determined the key parameters of the flow structure when a transition to unsteadiness occurs [662,663]. Computation of axisymmetric turbulent flows in rotor–stator type systems showed existence of traveling waves in the boundary layers and inertial waves in the core region [664]. Heat transfer with mass transfer in a cylinder with axial rotation established the effect of rotation on volume averaged temperature [665].

Melting and freezing between two rotating concentric cylinders were analyzed to obtain overall design parameters on heat transfer and cycle time [666,667]. The extension of this problem to the rotating layer of a eutectic material revealed the effects of Coriolis forces for both stationery and oscillatory convection [668]. Centrifugal phase separation was codified in terms of dimensionless groups and an expression for evaluation separation performance as developed [669].

Rotating drum dryers and reactors were analyzed for flow and heat transfer in connection with solid state fermentation with interesting results obtained for axial mixing and axial temperature gradients [670,671]. Double drum drying was similarly analyzed with emphasis on effects of drum temperatures, gap size, and thermal inertia on overall efficiency [672]. A new approach was developed to handle interparticle gas flow effects in rotary kilns, and results were successfully compared to experiments [673]. Granular flows comprising particles of different diameters were also analyzed for two-dimensional flow, and experiments generally verified the predicted overall flow structure [674]. Bed transition from slumping to rolling and bed turnover time were predicted for mono-size granules, and a new Froude number was proposed to correlate experiments for different materials [675]. Three-dimensional modeling of flow and heat transfer in a rotary lime kiln was compare to pilot plant experiments [676].

Heat, momentum, and mass transfer of a non-Newtonian fluid in single and twin-screw extruders were found to be dependent on conduction in the screw barrel [677].

10.4. Cylinders, spheres, and bodies of revolution

Crystal growth techniques remain an active area for fundamental investigation via experiments and theory. Experiments were reported on the Bridgman–Stockbarger method to determine the effect of melt stirring on crystal purity [678,679]. Numerical analyses of crystal growth rate in the Czochralski method predicted the interplay between magnetic field strength and rotation rate [680] and between internal radiative heat transfer and rotation rate [681]. Effects of a rotating magnetic field in a cylindrical silicon melt include a primary azimuthal flow and a secondary meridonal flow [682]. Numerical simulation of the effect of ampoule rotation on temperature and feed rates in the rotational Bridgman method showed that stirring effect of ampoule rotation was increased with an increase of rotation rate [683].

Modes of convection in a rotating cylinder under vertical, horizontal and rotating magnetic fields exhibit several flow regimes dominated by a subset of the field effects and rotational speed [684]. Analytical study of the stability of rotating magnetic fluid columns revealed modes and conditions for stability both with an without heat transfer [685]. Coherent flow structures generated by a rotating magnetic rod in agitated small tanks were obtained with an electrochemical probe using a power spectral density analysis of current fluctuations and flow visualization via laser tomography [686].

Heat transfer reduction at the separation point of a translating and spinning sphere was analyzed, and a significant reduction below stagnation point values was shown to be possible [687]. Temperature dependent viscosity effects on convection up to the transition point on a spinning sphere produced a marked effect on heat transfer coefficients [688].

11. Combined heat and mass transfer

11.1. Ablation

A number of studies consider the heat transfer, phase change, thermal effects of particles and thermoelastic wave of ablating materials. Heat transfer and phase change during picosecond laser ablation of nickel were investigated using both experimental and computational studies. Researchers determined the threshold fluence for mass removal (ablation) experimentally. Numerical calculations of transient temperature distribution and kinetics of solid–liquid and liquid–vapor phase change interfaces were performed [689,690]. A hybrid simulation was done to investigate metal ablation by still using picosecond laser pulses [691]. Researchers also developed a photochemical and photothermal model for pulsed-laser ablation [692]. In order to investigate the time evolution of nickel ablation induced by high-energy picosecond laser pulses, in situ photography was studied and the fundamental and second harmonic wavelengths were used for the pump and probe beams, respectively [693]. Researchers also formulated an analytical solution for thermoelastic waves in a metal induced by an ultrafast laser pulse in the form of a Fourier series [694]. A coupled aeroheating/ablation analysis for missile configurations has been done [695]. Usually shock-waves are generated during pulsed-laser ablation. The dynamic properties of shock-waves formed during laser ablation at sub-atmospheric pressures are studied [696]. Thermal effects of particles on hypersonic ablation were investigated [697]. Multiscale computational modeling of laser ablation was performed using two computational schemes, combined molecular dynamic-finite element method and the direct simulation of Monte Carlo method [698]. In practical applications, the ablation, pyrolysis gas formation and removal, and heat conduction phenomena at the stagnation point of the heat-shield for the four Pioneer–Venus vehicles are calculated to investigate the response of heat-shield material [699].

11.2. Transpiration

Two studies involving transpiration were performed. In order to predict the aero-thermal behavior of transpiration cooled plates, a multi-scale approach based on the homogenization method of periodic material structures is developed [700,701].

11.3. Film cooling

Film cooling is an effective method of heat transfer and very useful in protecting surfaces from effects of thermal stress. Several studies consider the effects of bulk flow pulsations on film cooling with compound angle holes [702,703] and the effect of embedded vortices on film cooling performance on a flat plate [704]. The film cooling performance was also studied. Researchers investigated film cooling effectiveness and heat transfer coefficient distributions around different diffusion shaped holes [705], flow visualization and film cooling effectiveness around shaped holes with compound angle orientations [706], transonic film cooling effectiveness from shaped holes on a simulated turbine airfoil [707], the film cooling performance on the pressure side of a turbine vane subjected to high mainstream turbulence levels, with and without showerhead blowing [708]. The heat flux reduction from film cooling, correlation of heat transfer coefficients and correlation of film cooling effectiveness from thermographic measurements at engine-like conditions were also investigated [709,710]. Experimental measurements of the performance of new film cooling hole geometry, the converging slot-hole or console were made [711,712]. An experimental investigation was conducted to improve a slot film cooling system used for the cooling of a gas turbine combustor liner [713]. An experiment was conducted on the flow and heat transfer characteristics of film coolant injected from a row of five holes with compound angle orientations [714]. Several numerical simulations have been done. A numerical simulation of blown film cooling was performed and suggested that the heat transfer rates were affected by many parameters [715]. Researchers also presented recent trends in modeling jets in crossflow with relevance to film cooling of turbine blades [716].

11.4. Jet impingement heat transfer—submerged jets

The heat transfer mechanism of multiple impinging jets with gas–solid suspensions has been investigated both experimentally and numerically, [717]. An experimental study of flow downstream of round, pitched and skewed wall jets (vortex generating jets) is presented to illustrate the effects of changing the geometric inlet conditions of the jet holes, [718]. Heat transfer augmentation of impinging jet-array with very small separation distances is attempted by using the grooved orifice plate through which the nozzles with different diameters are fitted [719]. The effect of jet inclination of the local heat transfer under an obliquely impinging round air jet striking on isothermal circular cylinder is experimentally investigated. The circumferential heat transfer distribution as well as axial Nusselt number is measured, [720]. A jet impingement technology to enhance heat transfer at the grinding zone, is presented. The jet impingement technology uses a new apparatus developed to spray grinding fluid onto the workpiece surface at the grinding zone from the radial holes of an electroplated CBN wheel [721]. It is shown that a self-oscillating impinging jet configuration is extremely beneficial in enhancing the heat removal performance of a conventional (stationary) impinging jet [722]. Stability analysis of the mechanism of jet attachment to walls is performed. The analysis makes it possible to formulate the separation distance of the jet depending on its properties at the blowing slot, [723]. A confined laminar swirling jet is studied and flow and temperature fields are simulated numerically using a control volume approach. Entropy analysis is carried out to determine the total entropy generation due to heat transfer and fluid friction [724]. The entropy generation is a plane turbulent jet is revised. This flow is characterized by quasi-periodic lateral oscillations, documented in the literature, due to the instability of the flow [725]. Measurements of mean and fluctuating velocity and temperature and their self- and cross-products to the third order are presented for a heated axisymmetric air jet [726]. The heat transfer characteristics of the flow downstream of a heated jet source of momentum issuing into an aligned uniform stream, is established. Perturbation solutions about limiting similarity states at the jet and downstream are obtained, [727]. The flow and heat transfer characteristics of impinging laminar multiple square jets have been investigated numerically through the solution of the three-dimensional Navier–Stokes and energy equations in steady-state [728]. A fully elliptic Navier–Stokes equation solver in conjunction with a Reynolds stress model is validated for mildly and strongly under-expanded jets [729]. A well-resolved numerical simulation of a Mach 0.5 jet exiting from a rectangular shaped nozzle with an aspect ratio of 5 into a quiescent ambient was performed at a Reynolds number of 2000 based on the narrow side of the nozzle [730]. The similarity equation describing the thermal boundary layers of laminar narrow axisymmetric jets is derived based on boundary layer assumptions. The equations are solved exactly [731]. Adaptive finite element computations of laminar jet impingement heat transfer are presented. Variable fluid properties and compressibility effects are considered. A unified formulation of the equations is used to treat the simultaneous presence of three flow regimes: incompressible, compressible, and anelastic [732]. Turbulent flow field and heat transfer in an array of slot jets impinging oil a moving surface have been numerically investigated using Large Eddy Simulations [733]. An experimental investigation has been conducted on the impingement of under-expanded, axisymmetric, and supersonic jets on flat plate. The surface pressure and the adiabatic wall temperature distributions on the flat plate have been measured in detail at small nozzle-to-plate distances [734]. An experimental study is carried out on gas mixing processes and heat transfer augmentation by a forced jet in a large cylindrical enclosure with an isothermal bottom heating/cooling surface, [735]. A numerical and experimental investigation on cooling of a solid surface was performed by studying the behavior of an impinging jet onto a fixed flat target [736]. A microjet impingement cooling device for high power electronics was constructed from silicon wafers using microelectromechanical systems fabrication technique [737]. Impinging jet combusting flows on granite plates are studied. A mathematical model for calculating heat release in turbulent impinging premixed flames is developed. The combustion including radiative heat transfer and local extinction effects, and flow characteristics are modeled using a finite volume computational approach and two different eddy viscosity turbulence models [738]. A three-dimensional mathematical model has been developed for the simulation of industrial-scale flaming processes. Results are presented from the application of this model in a natural gas jet flame impinging vertically on the surface of granite material. The aim is to obtain a deeper insight into the flame characteristics, [739]. Carrier gas flow in a rapid thermal chemical vapor deposition reactor was studied using flow visualization and laser induced Rayleigh light scattering. The flow field consists of a downward axisymmetric jet of carrier gas impinging on a wafer which undergoes transient heating, [740]. The heat transfer process is investigated utilizing a three-dimensional finite volume numerical method and renormalization group theory based k-epsilon turbulence model. The issuing incompressible jet is impinging upon the inside of an inclined surface creating a thermal boundary layer and a fully three-dimensional vortex structure [741]. Rectangular jet impingement heat transfer on vehicle windshield is examined [742]. Two-dimensional axisymmetric flow and energy equations are solved numerically using a control volume approach for the case of a gas assisted laser heating of steel surfaces. Various turbulence models are tested [743]. A mathematical model for the calculation of the hydrodynamic and thermal parameters of dispersed impurity in a round pipe and in a jet is given in Eulerian variables. The model is based on a unified set of equations describing the turbulent characteristics of particles in non-isothermal flow and of boundary conditions representing the interaction of the particles with the rough channel surface and the boundary of submerged jet [744]. Heat transfer and flow visualization experiments were performed to investigate the performance of swirling and multi-channel impinging jets and compare the results with those of a multi-channel impinging jet and conventional impinging jet at the same conditions [745]. The heated-thin-foil technique is used jointly with infrared thermography to evaluate accurately the heat transfer characteristics of one row of jets impinging on a flat plate. The impingement is confined by the test section and spent air is constrained to exit in only one direction, [746]. Experimental investigation of convective heat transfer under arrays of impinging air jets from slots and circular holes is performed. The aim is to develop the relationship between heat transfer coefficient, air mass flow and fan power which is required for the optimum design of nozzle systems [747]. In conventional drying of coated substrates air impingement is usually employed. Because of the high-velocity air flow, most of the heat is transfered by convection and the heat transfer coefficient is not uniform, leading to drying defects. To overcome this and achieve a high uniform heat transfer coefficient, the energy, is supplied to the back side of the substrate by conduction through a thin air-layer between a heated plate and the moving substrate [748]. Surface heat transfer characteristics of a heated slot jet impinging on a semicircular convex surface have been investigated by using the transient heating liquid crystal technique [749]. A combined buoyancy and inertia driven vortex flow in an air jet impinging onto a heated circular plate confined in a cylindrical chamber is visualized [750]. The self-sustained oscillating flow (vortex dynamics and energy transport) induced by a plane jet impinging upon a smaller circular cylinder located in the jet centerline within the potential core region is experimentally examined [751]. Experiments were performed to study the heat transfer characteristics of a premixed butane/air slot flame jet impinging normally on a horizontal rectangular plate. The effects of the Reynolds number and the nozzle-to-plate distance on heat transfer were examined [752]. Detailed heat transfer distributions are presented over a jet impingement target surface with dimples. The effects of jet impingement, as an extremely effective heat transfer enhancement technique, on a target surface with a dimple pattern is investigated, [753]. Numerical predictions of turbulent plane discharged normal to a weak or moderate cross-stream are proposed. The Reynolds-averaged Navier–Stokes equations along with a standard k-epsilon turbulence model have been used to formulate the flow problem [754]. Heat transfer enhancement by the perforated installed between an impinging jet and the target plate is investigated [755]. Turbulent heat transfer from a flat surface to a swirling round impinging jet is studied [756]. Measurements of a plane jet impinging onto a normal flat plate placed up to five jet widths from the jet outlets are presented. The small spacing ensured that the stagnation streamline remained in the potential core of the jet [757]. Direct numerical simulations of an unsteady impinging jet are performed to study momentum and heat transfer characteristics. The unsteady compressible Navier–Stokes equations are solved using a high-order finite difference method with non-reflecting boundary conditions [758]. A numerical finite difference approach was used to compute the steady and unsteady flow and heat transfer due to a confined two-dimensional slot jet impinging on an isothermal plate [759]. Laminar impinging flow heat transfer is considered with a purely viscous inelastic fluid. The rheology of the fluid is modeled using a strain rate dependent viscosity coupled with asymptotic Newtonian behavior in the zero shear limit. The velocity and temperature fields are computed numerically for a confined laminar axisymmetric impinging flow [760]. In previous studies, the enhanced cooling in the second pass of a serpentine channel was achieved by a combination of impingement and cross-flow induced swirl. In a continuing study, the focus is to enhance the heat transfer in the first pass of the two-pass channel using traditional rib turbulators [761]. The results of a computational fluid dynamic model is presented fro heat transfer under a semi-confined slot turbulent jet under thermal boundary conditions such that the temperature-dependence of the fluid properties affects the flow and thermal fields. A comparative analysis in the turbulent flow regimes is made of the standard k-epsilon and Reynolds stress turbulence models for constant target surface temperature [762]. Simulation results are presented for a single semi-confined turbulent slot jet impinging normally on a flat plate. Effects of turbulence models, near wall functions, jet turbulence, jet Reynolds number, as well as the type of thermal boundary condition at the target surface are discussed in the light of experimental data [763].

A novel micromachined flow sensor capable of detecting small amounts of volumetric flow rates and extra-low flow velocities is developed. The innovative flow sensor detects a periodic flapping motion of a planar jet impinging on a V-shaped plate downstream [764].

11.5. Jet impingement heat transfer—liquid jets

Analytical research was conducted to study the heat transfer from horizontal surfaces to normally impinging circular free-surface jets under arbitrary-heat-flux conditions [765]. A numerical model is presented for the mixing of an inclined submerged heated plane water jet in calm fluid, which has some improvements over similar models presented by various other investigators [766]. The flow and heat transfer characteristics of impinging laminar square twin jets have been investigated numerically through the solution of three-dimensional Navier–Stokes and energy equations in a steady-states [767]. A method is presented which utilizes the hue-angle method to process the color images captured from the liquid crystal color play. Instantaneous temperature readings from embedded thermocouples were utilized for in situ calibration of hue angle for each data set [768]. Experiments have been performed to assess the impact of an extended surface on the heat transfer enhancement for axisymmetric, turbulent liquid jet impingement on a heated round disk [769]. The experimental details, data acquisition and data handling techniques are presented for steel plates during water jet impingement by one circular water jet from an industrial header [770].

11.6. Sprays

Artificial neutral networks (ANN) models have been developed and applied to free propane sprays and to water spray cooling heat flux predictions. For the propane spray conditions the ANN model is trained against the computational fluid dynamics results and verified against experimental data [771]. The dynamic modeling of a spray dryer is suggested to be considered as series of well-stirred dryers. That is, a series of dryers in which the output variables are equal to the state variables. The state equations were obtained from the heat and water mass balances in product and air. Additionally, heat and water mass balances in interface jointly with water equilibrium relation between product and air were considered [772]. Spray impingement and fuel formation models with cavitation have been developed and incorporated into the computational fluid dynamics code, STAR-CD. The spray/wall interaction process was modeled by considering the effects of surface temperature conditions and fuel film formation [773].

11.7. Drying

A numerical code that can predict vacuum freeze drying processes in trays and vials was developed using finite volume method. A moving grid system is employed to handle irregular and continuously changing physical domains encountered during the primary drying stage [774]. Finite element method is employed to solve the non-linear unsteady partial differential equations describing two-dimensional temperature and moisture distributions within a single rice kernel during drying and tempering processes [775]. A mathematical model of coupled heat and mass transfer was applied to batch fluidized-bed drying with microwave heating of a heat sensitive material-carrot. Four kinds of microwave heating with intermittent variation were examined [776]. The effects of superheated steam temperature and convective heat transfer coefficient on the drying rate and product quality attributes (shrinkage, density, porosity, color, texture, and nutrition loss) of potato chips was investigated [777]. A transient two-dimensional mathematical model is developed to simulate the through-air drying process for tufted textile materials. The heat transfer in a cylindrical porous medium and the air flowing around it are analyzed separately [778]. A simplified model for drying solids in the constant rate period in a batch fluidised bed was developed. It assumes the bed to be divided into dense and bubble phases with heat and mass transfer between the phases [779]. Thermal modeling of the fluidized bed drying of wet particles is considered to study heat and mass transfer aspects and drying thermal efficiencies [780]. The measuring method of the thermal conductivity and water contents for single seed is experimentally studied. Also an interrelated curve between the thermal conductivity and water contents for single seed is obtained [781]. The theory behind a fluidized bed fast-drying method is investigated as a potential time-saving process, which can reduce overall drying time compared to single temperature cycles [782]. The heat-up and the drying of a packed bed consisting of large wood particles as encountered in furnaces are measured and compared to the predictions of a particle resolved approach [783]. A detailed study of the drying kinetics for a range of milk products has been conducted [784]. A study on the drying of thin layers of polymer solution containing two volatile solvents is performed through experiments and numerical simulations [785]. A simplified procedure for modeling the performance of a low temperature heat pump dryer was developed. The system modeled consists of a vapor compression heat pump coupled to a continuous cross flow bed dryer [786]. High performance packing, namely, structured packing that has good heat and mass transfer characteristics, is proposed for dehumidification of air using liquid desiccants and for regeneration of liquid desiccants [787]. Numerical simulation of convection-microwave drying for a shrinking, discretely non-homogeneous material is performed using finite element technique [788]. Drying of multi-dimensional food products is investigated analytically. A simple method is developed for the determination of drying time of multi-dimensional products using drying parameters that are available from the literature or can be determined experimentally [789]. A simple graphical method is proposed to determine the drying moisture transfer parameters such as moisture diffusivity and moisture transfer coefficient for solid products [790]. Drying of sawdust in an atmospheric pressure spouted bed stream dryer is studied and the possibility to control the outgoing moisture content using the exhaust temperature as a control parameter is examined [791]. A control volume formulation for the solution of a set of two-way coupled heat and diffusive moisture transfer equations with an infrared source term is presented in three dimensions [792]. A thin film dryer (TFD) device has been used to study the drying behavior of viscous products and their water diffusivities. The thin product film was dried convectively in different conditions [793]. A dimensionless analysis for the detailed equations of heat and mass transfer during food drying was developed. This analysis was carried out in tensor form of the equations. Some reported and non-reported dimensionless groups were deducted which were used to estimate the mechanisms that control heat and mass transfer during food drying [794]. Three types of mathematical models have been developed for the simulation of kiln drying of softwood lumber and the simulation of drying stresses: a single board-drying model, akiln-wide drying model and a drying stress model [795]. Numerous experimental data are generalized to calculate the basic characteristics (excess vapor pressure, time of pressure setting, vapor flux) of high-intensity drying with internal heat sources. The role of pressure-gradient mass transfer is discussed [796]. Numerical simulation of static-bed drying of barley is performed [797]. A mathematical model for continuous drying of grains in a spouted bed dryer has been presented to predict moisture content, air and grain temperatures as well as energy consumption [798]. An overview of the applications of the discrete element method (DEM) in gas–solid flow systems is presented, discussing further development of this technique in the application of drying particulate solids [799]. The results of theoretical and experimental studies on drying of aqueous suspensions of finely dispersed solids sprayed over the surface of an inert ceramic sphere are presented [800]. X-ray microtomography is proposed as a new tool to investigate the evolution of size, shape, and texture of soft materials during a drying operation. This study is focused on the drying of mechanically dewatered sludges from a secondary wastewater treatment [801]. The drying rates of zeolite pellets in spouted beds and in conventional fan assisted ovens are studied [802]. Two dimensional heat and mass flux equations were used to describe preheating process during wood drying. Mathematical formulae of heat and moisture transfer to wood were developed [803]. A comprehensive study of the impingement heat transfer coefficient at high temperatures is carried out and presented in this paper. The aim of the study is to give a summary of the experimental results of the impingement heat transfer covering a impingement air temperature range [804]. Reanalysis of the drying background in wheat showed that analytical solutions may be employed in this grain to estimate diffusion coefficients by using the simplified equation for short times instead of the time-consuming series [805]. An improved numerical heat transfer model has been developed for a rotary kiln used for drying and preheating of wet iron ore [806]. Development and validation of mathematical models based on heat and mass transfer principles for freeze-drying of vegetable slices are performed [807]. A two-dimensional finite element model was used to analyze isothermal thin layer drying of wheat representing the grains as axisymmetric ellipsoids. The effects of diffusion coefficient was estimated by minimizing the sum of squares of the residuals between numerically predicted and experimental moistures [808]. An experimental set up specially designed for the investigation of drying kinetics, of heat transfer coefficient evolution, and of the mechanical torque necessary for stirring. This device was applied to municipal sewage sludge. Experiments were performed to investigate the influence of aging of sludge on the drying kinetics [809]. A newly developed Biot–Reynolds correlation to determine the moisture transfer parameters is presented. The development is based on the experimental data taken from various sources in the literature [810]. A recently developed Biot–Dincer correlation for drying applications is presented. The developed correlation is used to determine the moisture diffusivities and moisture transfer coefficients for products subjected to drying

[811]. Modeling of coupled heat and mass transfer during convective drying of wood is performed [812].

11.8. Miscellaneous

A variety of studies in which heat and mass transfer occurs in combination have been performed. These included the cooking of foods [813–817], absorption [818], combustion and flames [819–821], chemical reacting flows [822,823], and two/multiple-phase flows [824–827]. Thermophoresis of particles in gas-particle two-phase flow with radiation effect is studied [828]. Modeling of frost growth and frost properties with airflow over a flat plate [829] was performed. An engineering model for coupled heat and mass transfer analysis in heated concrete was established [830]. A mathematical model for description of coupled mechanical, thermal and diffusive processes in semitransparent amorphous solid with molecular gaseous admixture subjected to thermal infrared radiation was developed [831]. Heat transfer in combustors [832] and heat transfer in an aircraft nacelle anti-icing system [833] were also studied. Researchers also studied cylindrical pin-fin fan-sink heat transfer and pressure drop correlations [834].

12. Bioheat transfer

The present review is only a small portion of the overall literature in this area. This represents work predominantly in engineering journals with occasional basic science and biomedical journals included. This is a very dynamic and cross disciplinary area of research, and thus, this review should be taken as more of an overview, particularly from an engineering point of view, rather than an exhaustive list of all work in this area for this year. Subsections include work in cryobiology including preservation, thermal therapies as well as hyperthermic biology with thermal therapies and burn injury. Further sections dealing with thermal properties, thermal comfort/regulation and general papers are presented.

12.1. Cryobiology

Heat transfer work in the area of cryobiology falls broadly into the area of cryopreservation and cryosurgery which seek to either preserve or destroy cells or tissues by cooling or freezing. Traditional cryopreservation of engineered tissues was numerically studied by Cui [835], while an analysis of freeze-drying in vials was presented by Brulls [836]. Although cryopreservation usually is intended to maintain the biological viability of the material, one offshoot of this is also to preserve ultrastructual integrity for electron microscopy by extremely rapid freezing. This has been applied to the study of polysaccharide ultrastructures in hydrogels [837]. Basic studies of latent heat evolution during freezing of cryobiologically relevant solutions and during cellular dehydration and intracellular ice formation in tissues was presented by Devireddy [838,839].

Studies relevant to hypothermic tissue preservation include a method to control brain temperature [840], as well as the effect of lowering temperature on the oxygen transport during brain hypothermia resuscitation [841]. The characterization of a novel intravascular catheter for induction and reversal of hypothermia in a porcine model was also presented [842]. A method for estimation of time-dependent surface heat flux due to cryogen spray cooling in laser treatments was presented [843]. Lastly, studies relevant to cryosurgery investigated the freezing and thawing of skin [844], and the thawing of multiple frozen regions simultaneously [845].

12.2. Hyperthermic biology

12.2.1. Thermal therapies

Thermal therapies usually include one or more sources of power being delivered locally to treat tissue by reaching hyperthermic temperatures. The normal energy sources include laser, radiofrequency (RF), microwave, and high intensity focused ultrasound. Studies in the laser area include heat transfer characteristics of bio-materials irradiated by pulsed-laser [846]; the effect of thermal lensing during selective photothermolysis [847]; spray cooling efficiency during port wine stain laser treatments [848]; and a study of residual thermal damage, ablation, and wound healing as a function of erbium laser pulse duration [849]. A finite element analysis of constant-power invasive microwave coagulation of liver tumors was presented [850]. Radiofrequency studies included work on a test apparatus for evaluating the heating pattern of radiofrequency ablation devices [851] and the evaluation of RF treatment of tonsillar hypertrophy [852]. General work in hyperthermic thermal therapies included estimation of heat transfer and temperature rise in partial-body regions during MR procedures [853]; three-dimensional modelling and optimization of thermal fields induced during hyperthermia [854]; thermal dose optimization in hyperthermia treatments by using the conjugate gradient method [855]; and W-band investigation of material parameters, SAR distribution, and thermal response in human tissue [856]. In addition, several studies on the prediction of burn injuries in the skin were presented [857,858].

Novel methods of hyperthermic treatment include using magnetic fluid hyperthermia which was evaluated under accelerated simulation conditions [859]; a field-focusing device to increase power output of thermorod (TM) implants for thermal ablation of tissue [860]; and the study of a synergistic cell-killing by combination of hyperthermia and heavy ion beam irradiation for refractory cancers [861]. Additionally, a novel design for a mammary gland tumor phantom for microwave radiometry was constructed [862].

12.2.2. Thermal properties

Thermal property work focused on blood flow as well as conductivity and specific heat measurements as well as novel mechanisms of heat flow using nanofluidics. These included the determination of thermal diffusivity of mortadella using actual cooking process data [863]; while the precooking and cooling of skipjack tuna was also studied numerically [864]. A method using sinusoidal heating to non-invasively measure tissue perfusion was introduced [865]. Also the mechanisms of heat flow in suspensions of nanosized particles (nanofluids) was studied [866].

12.2.3. Thermal regulation/comfort

Thermal regulation is important for all living animals, but is especially important clinically for premature infants and patients undergoing surgery who have impaired thermoregulatory mechanisms. To address this warming systems with upper body blankets using a copper manikin of the human body were compared by Brauer [867]. In premature infants unsteady heat conduction was studied numerically [868]; and by experimental and numerical studies for convective heat transfer in a neonatal incubator [869]. In addition, a special warming blanket to prevent core hypothermia during major neonatal surgery was also presented [870]. Work in animals included a model of respiratory heat loss in the sheep [871]; in-vivo non-invasive study of the thermoregulatory function of the blood vessels in the rat tail using magnetic resonance angiography [872]; and the effect of environmental temperature on body temperature and metabolic heat production in a heterothermic rodent [873]. Evaluation of thermal comfort using a combined multi-node thermoregulation and radiation model with computational fluid dynamics (CFD) was also presented [874].

12.2.4. General/miscellaneous

General work included a Boussinesq model of natural convection in the human eye and the formation of Krukenberg's spindle [875]; and a new fundamental bioheat equation for muscle tissue [876].

13. Change of phase—boiling and evaporation

Papers on boiling change of phase for 2002 have been categorized as follows: droplet and film evaporation, bubble characteristics and boiling incipience, pool boiling, film boiling, flow or forced convection boiling and two-phase thermohydrodynamic phenomena. These topics are discussed in their respective subsections below.

13.1. Droplet and film evaporation

Papers in this category discuss such areas as droplet heat transfer, film heat transfer and spray cooling.

The effects of spray parameters on critical heat flux (CHF) in subcooled spray cooling were documented experimentally [877]. For a hot plate facing upward being cooled with impinging water droplets [878] the authors note the importance of droplet internal fluid motion. The isotropic turbulence flow field effect on single liquid droplet evaporation was correlated [879] for mono- and bi-component droplets. Droplet evaporation in the drying of a salt solution in a pulsating flow was experimentally evaluated [880]. Pulsation led to high evaporation rates and short drying times. Evaporation of acoustically levitated droplets of binary liquid mixtures was modeled [881]. The effects of acoustic streaming near the droplet surface were discussed. A spray cooling experiment [882] showed the importance of the interaction of the departing bubbles and the impinging droplets. A model was used to describe the effect of a near-wall droplet-free zone [883]. Heat transfer in internal flows through pipes showed enhancement due to elbows [884]. The influence of Marangoni convection in a two-component flow with droplets was described [885]. The velocity field, as driven by Marangoni flow, was measured by monitoring the motion of tracers within the droplet [886]. A numerical study showed the effects of fluid properties on cooling of a plate with a mist spray [887].

Droplet evaporation in porous and non-porous surfaces was experimentally evaluated [888]. The importance of radiation was noted. Evaporation on a wall screen was documented [889]. Enhancement over single phase flow was noted. The effects of roughness on droplet impingement heat transfer were discussed with emphasis on the contact angle and interfacial behavior [890]. The effects of heating on the advancing and receding contact angles were noted. Quenching of steel plates was experimentally documented [891]. The sensitivities to some flow parameters were quantified. The evolution of the liquid film under the droplet on a steel surface was documented [892]. Fluids of various properties were tested. Existing models which describe the liquid film behavior were considered to be inadequate.

Modeling of an evaporating droplet stream was supported by measuring the energy budget using optical methods [893] and a model for describing the deforming interfaces during droplet impingement was presented [894]. The attributes of the measurement method were presented. The effects of pressure and temperature non-uniformities on surface tension in non-equilibrium liquid-gas flows were discussed [895]. High evaporation rates require large corrections in surface tension values. Simulation methods to be applied to combusting flows were developed [896] for application to a sudden-expansion combustor.

A fringe-probing method for measuring the contact diameter and microdroplet diameter in droplet-impacting flow was presented [897] and the value of using a two-color, laser-induced fluorescence method for documenting the temperature field around evaporating drops was discussed [898]. The latter revealed two distinct phases of droplet evaporation, the first is a rapid temperature drop and the second is with a reduced cooling rate due to the enhanced fuel vapor concentration at the surface.

The effect of heat transfer to a supporting fiber on droplet evaporation was experimentally evaluated [899]. Calculations of enhancement due to conduction to the fiber were in agreement with the experimental results. Drying with superheated steam was theoretically addressed [900]. Results were presented in terms of an inversion temperature where the dry air and superheated steam drying rates matched. Freezing of water droplets due to evaporation in a heat storage device was described [901]. The system is to store "cold" from LNG liquefaction plants.

Falling film evaporation with non-Newtonian fluids was numerically evaluated [902]. Larger heat transfer coefficients were found with higher concentrations of the solution. Film evaporation with dissolved solids and highly viscous liquids was modeled [903]. Falling film evaporation rates were predicted. Molecular dynamic simulations were used to compute ultra-thin layer evaporation of argon on a surface [904] when the surface temperature was rapidly raised. Cooling from high surface temperatures created an unstable vapor film that deformed to form spherical shapes. Evaporation of liquid jets in gas–solid suspension flows was studied parametrically [905]. Film evaporation rates inside a vertical tube were measured with fluids of various properties [906]. Ranges of suitability of a certain correlations for heat transfer coefficients were given in terms of values of dimensionless groups.

Film evaporation of HCFC22 inside horizontal tubes was evaluated and optimal geometries for the placing of spiral fins on the surface were documented [907]. The effects of capillary tube radius on evaporation of the thin liquid film and meniscus were modeled [908]. Heat transfer was by conduction through the liquid film and evaporation at the interface. Evaporation of thin liquid falling films on bundles of enhanced-surface tubes was discussed in terms of the liquid flow patterns which were shown to vary with liquid flow rates [909]. Salt/water mixture falling film evaporation on roll-worked, enhanced tubes and tube bundles were experimentally evaluated [910]. Enhancement via this low-cost surface preparation was recorded to be comparable to the more expensive commercial enhanced surfaces for boiling. Evaporation inside of smooth and enhanced-surface tubes was experimentally evaluated [911] to document the performance of the enhanced surfaces. Evaporation from V-shaped microgrooves was evaluated [912]. The effects of axial flow through the microgroove when the tube was strongly inclined were documented. Liquid evaporation in isotropic porous media with non-Darcy flow effects was analytically described [913]. The evaporation rates are more pronounced when large inertial effects are present.

Calculations were presented for the evaporation rate of water from undisturbed pools [914]. Correlations were tested against data from several sources. Heat transfer and evaporation in a pool fire were computed [915]. Effects of lip height and flame emissive power were discussed. Flash evaporation with a sudden pressure drop was described by experiments [916]. A correlation between the mass evaporated by flashing and the superheat of the flow was developed.

The influence of the flowfield on heat transfer to a sliding bubble was analyzed and measured [917]. Unless vaporization rates are high, the film thickness was found to be determined by flow phenomena rather than by heat transfer. Breakup of an evaporating film falling down a vertical wall was analyzed [918]. The influences of important parameters, such as Marangoni number and Reynolds number, were evaluated. The effect of pulsing the heat source on the evaporation of superfluid helium was measured [919]. Evaporation was caused by second sound thermal shock onto the free surface.

A model was developed for evaporative film cooling on a vertical, rectangular channel [920]. Included in the investigation was assessment of using a multipurpose commercial CFD code for simulating mass transfer phenomena in the nuclear field. Molecular dynamic modeling was applied to simulations of two-component fluids [921]. In was shown that irreversible thermodynamic theory can be used to describe transport phenomena.

The relative importance of heat and mass transfer in drying was assessed via a model [922] and the cooling of birds by cutaneous water evaporation was described [923].

13.2. Bubble characteristics and boiling incipience

Evaporation of a constrained bubble was modeled [924]. Evaporation near the contact line was balanced by condensation in the colder regions. The time-dependent behavior was described for cases of small capillary number. Nucleate boiling off a fine wire was experimentally described in terms of jetting of the departing vapor bubbles [925]. Several different jetting regimes were identified and it was noted that vapor departure is quite different than usually seen in nucleate boiling. Bubble characteristics of two-phase flow in large-diameter pipes were observed [926]. Probability density function (PDF) description of the bubble flow was used to document a short development length. Experimental documentation of bubble behavior, including bubble growth rates and time of attachment, was used to characterize transition from partially- to fully-developed subcooled flow boiling [927].

Bubble behavior in subcooled flow boiling in upward flow was experimentally documented [928]. This behavior, in terms of growth rates and variation of bubble lifetime, was correlated with flow parameters. Single sliding bubble behavior was experimentally documented [929] and related to the gravity level. In a related experiment, the behavior of a single bubble sliding on a downward-facing heated surface was documented [930]. A numerical solution was presented which describes bubble merger events from a single nucleation site [931]. The pattern was shown to compare well with experimental observations. A model based upon pseudo-equilibrium was used to describe heat transfer in boiling liquids, including the bubble formation and relaxation stages of the bubble cycle [932]. A method was presented to describe the transient behavior of ultra-fast heating with a pulsed laser beam [933]. Wave-type heat transfer as a shock wave, with wave change, was simulated.

The flow structure of a wake behind a bubble was visualized with a Schlieren optical technique [934]. Mass transfer around a bubble during surface nucleate boiling, including vaporization and condensation processes around the bubble, was investigated analytically [935]. Experiments showed a thermal jet at the cap of the bubble due to interfacial vapor condensation.

Thermodynamic bifurcation models were used to describe transitions among different boiling modes caused by interactions among active sites or dry patches [936]. A non-linear non-equilibrium statistical thermodynamics model was used to predict phase transition caused by the interaction among active sites or bubbles [937]. Measurements were taken to describe the effects of decreasing the distance between active nucleation sites [938]. The results were used to describe the interaction between competing sites. The influences of active sites on one another were shown to be mutual. Detailed measurements were taken on tiny resistors to document bubble nucleation on microsurfaces [939]. A first-order model for nucleation in the microscale was proposed. Data on incipience in microchannels were analyzed [940]. Thermocapillary forces tend to suppress the microbubbles that form in the wall cavities. Incipience of boiling in microchannels was experimentally documented [941]. The likelihood of bubbles growing sufficiently large to engulf the entire flow area of the microchannel was assessed. The effects of surfactants on subcooled boiling hysteresis were experimentally documented [942]. Boiling hysteresis features were recorded for degraded solutions.

Bubble motion control by ultrasonic waves was investigated experimentally and analytically [943]. The motion and equilibrium positions were predicted by solving the Rayleigh–Pleset equation and bubble motion equation. Photoacoustic cavitation was computed using a finite element method [944]. Guidelines were offered for reducing the occurrence of cavitation and extending the useful duration of a temperature jump. The effects of liquid metal magnetohydrodynamic (MHD) forces on the deformation and breakup of bubbles were computed [945]. A diagram for stability and breakup was created. Boiling of magnetic fluids in heat pipe applications was observed [946]. Degradation of the fluid during boiling was documented.

A model was presented for interfacial forces in bubbly flow in vertical channels [947]. The model predicted the lateral phase distribution in vertical channels. Experimental methods for documenting interfacial structures were presented [948]. The relative merits of the probes tested and visualization techniques were offered. Accuracy of measurements of apparent contact angle in a constrained vapor bubble heat exchanger was discussed [949]. Improved techniques were presented. The influence of dispersion forces on phase equilibrium between thin liquid films and their vapor was discussed [950]. The Gibbs assumption of a geometrical interface was shown to not hold. The internal pressure field of a violently collapsing bubble was computed with direct numerical solution of the Navier–Stokes equations [951]. Criteria required for application of a uniform pressure assumption were presented.

Experimental results were presented for direct contact heat and mass transfer of air bubbles in a hot water layer [952]. Air bubble flow patterns were identified and classified.

13.3. Pool boiling

Results of subcooled boiling experiments on a corrugated plate vertical heat exchanger were presented [953]. The data showed a change in the boiling curves at the onset of nucleate boiling. The effects of roughness of horizontally- and vertically-oriented ribbon heaters were documented [954]. Different surface treatments were used to create different roughness features. Improvement of boiling with a special boiling surface in a horizontal kettle boiler was experimentally evaluated [955]. Heat transfer coefficients reached five times the plane tube values. Boiling on plasma spray coated surfaces was evaluated for R-134a and R-600a [956]. Measurements included departure diameters, velocities and frequencies and nucleation site densities. The boiling crisis was experimentally evaluated on vapor-deposited, submicron metallic films [957]. A stark difference between performance on fresh and aged heaters was revealed. A study on the same surface investigated dryout and burnout [958]. Nucleate boiling enhancement on microporous surfaces in saturated FC-72 was documented [959]. The increased nucleation site density yielded increased hydrodynamic stability from increased vapor inertia and the CHF values were enhanced by the microporous surface. The structure had pores that interconnected the microchannels of the microporous structures to enhance nucleation [960]. High speed photography was used to characterize pool boiling from a tubular heater surface with structured re-entrant cavities [961]. In another study on coated porous surfaces, the effects of channel shape were evaluated [962]. Heat transfer performance was improved if the channels were open. Boiling on a porous metallic coating was experimentally documented [963]. Burnout heat fluxes were shown to be nearly independent of the surface finish. The value of having micro pin fins or submicron scale roughness elements on the surface was experimentally assessed [964]. In the high heat flux region, the pin fin with submicron roughness on it showed the best performance. Boiling with a square pin fin array was measured [965]. Twelve extended surfaces were tested. Screwed fins were tested in saturated pool nucleate boiling [966]. The interstices between the heating surface and the screwed fins were found to supply the bubble nuclei.

Boiling with binary mixtures was experimentally evaluated [967]. Both binary and ternary mixtures showed lower heat transfer coefficients than ideal values calculated from a mole fraction average of the wall superheats of pure components. Measurements of heat transfer coefficients of a mixture of ammonia and water on a horizontal heated wire were made [968]. The coefficients in the mixtures were markedly less than those in single-component substances. Experiments on bubble growth in He-3 at 1 K were presented [969]. The bubbles were spheroid-like due to the low surface tension. Predictions of boiling with additives were analyzed with neural network analysis [970]. The training accuracy was shown to be 100% accurate for the data set tested. An analytical model was applied to nucleate pool boiling with surfactant additives [971]. The effects of surfactant addition were described in terms of the manner by which it concentrates on the interface [972]. The effects of surface wettability on nucleate pool boiling with surfactant solutions were measured [973]. Effects of roughness were also addressed. The effects of bulk lubrication concentration on excess surface density with R123 pool boiling on a roughened surface were measured [974]. The excess lubricant, which resides in a very thin layer on the surface, influences boiling performance. Another paper [975] explained the technique used for the measurements, a spectrofluorometer.

The effects of an applied acoustic cavitation field were analyzed [976]. Acoustic cavitation enhanced the boiling heat transfer remarkably. A companion paper discussed the effects of cavitation on the nucleation, growth and collapse of bubbles [977]. Another paper on the same topic discussed the effects of adding nanometer granules to the flow [978]. The granules weakened the generation of bubbles. The effects on bubble dynamics of an applied electric field were visualized [979]. For a given heat flux, the electric field reduced the surface temperature. Measurements of the influence of an electric field were conducted in a low-gravity environment [980]. With sufficiently intense electric field, heat transfer coefficients and CHF values of 1 g boiling were attained.

Boiling on a vertical row of horizontal tubes was measured [981]. The model developed was shown to apply to a variety of fluids. The effects of diameter on small horizontal tubes were measured [982]. Conventional pool boiling correlations yielded acceptable results. A dynamic microlayer model was developed to describe the stages of the bubble cycle for experiments with boiling off a wire [983]. The boiling behavior for a vertical annular crevice was experimentally documented [984,985]. The annular geometry gave increased heat transfer coefficients at moderate heat fluxes compared to single tube data. Measurements were made for boiling in a vertical, small-diameter tube under natural circulation [986].

A microlayer model presented to describe transient pool boiling indicated conditions in which there can be direct transition from non-boiling to film boiling [987]. A model was given to predict contact line length at CHF [988]. Nucleation site density was measured with video pictures in support of the model. A model was developed for describing the growth of a bubble under transient pool boiling conditions [989]. The effect of the initial radius of the bubble was discussed.

A spatio-temporal analysis of nucleate pool boiling was developed [990]. Nucleation sites were identified using non-orthogonal empirical functions. Data were obtained with liquid crystal thermography and high speed video. Dynamic heating was studied in a microgravity environment [991]. A pure fluid was heated near the critical point and an unusual process was recorded where the vapor phase temperature can pass well beyond the temperature of the heating walls. Highly subcooled pool boiling measurements were taken in gravity-fields that ranged from micrograms to 2 g [992]. There was little effect of gravity on wall superheats below a given temperature even though there was a large effect of gravity on the bubble behavior. Strong Marangoni convection was observed at low-gravity. Similar measurements were taken on small heaters [993]. Boiling was dominated by the formation of a large primary bubble on the surface which acted as a sink for smaller surrounding bubbles. Dryout was under the primary bubble.

Bubble dynamics on microheaters was documented to describe coalescence of bubbles [994]. Coalescence was when the bubbles grow to a certain size that allows them to touch each other. A microlayer model was used to predict CHF in subcooled pool boiling [995] and fully developed nucleate boiling heat transfer [996]. Simulations of CHF in non-heating experiments were effected by controlled air flow through holes in the simulated boiling surface [997]. It was suggested that this method is a convenient one to measure CHF without an expensive facility. An analogy between boiling heat transfer and dissolution of a gas under a vacuum was discussed [998].

13.4. Film boiling

A mechanistic model of the Leidenfrost point was presented [999]. The models could be applied to both pools of liquid and sessile droplets and can be applied to rough surfaces. Forced convection film boiling was experimentally studied [1000]. The influence of subcooling was documented and rewetting dynamics were described. Fog cooling of hot surfaces was measured [1001]. Strong effects of cleanliness were identified. Bubble growth mechanisms were numerically simulated to describe film boiling processes [1002]. Gravity and surface tension effects were discussed. Numerical analyses, including conjugate heat transfer, were employed to evaluate film boiling on horizontal surfaces [1003]. The effects of energy exchange between a horizontal solid wall and the boiling fluid during saturated film boiling were described. An analysis of the stability of a vapor film on a hot wall under subcooled film boiling conditions was described [1004]. Measured film boiling data on horizontal cylinders were correlated for water and Freon 113 [1005].

13.5. Flow boiling

A two-phase flow pattern map for horizontal flow boiling was presented [1006]. It was used to predict onset of dryout at the top of the tube. The circumferential variation of heat transfer coefficient during in-tube evaporation for R-22 and R-407C was documented experimentally by using liquid crystals [1007]. Strong variations were noted when the heat transfer coefficients were high. A flow pattern dependent heat transfer model for a horizontal tube was developed and compared with data [1008]. It was show to accurately model heat transfer during evaporation with selected refrigerants. Experimental results described pressure drop, heat transfer and CHF in a small-diameter horizontal tube [1009]. Modifications to a two-phase pressure multiplier correlation were needed. Experimental results were used to describe heat transfer and pressure drop in narrow rectangular channels that might be applied in electronic cooling systems [1010]. Onset of flow instabilities and CHF when using multiple horizontal passages were investigated [1011]. Boiling two-phase heat transfer of LN_2 in downward flow in a pipe was experimentally documented [1012]. An estimation method for prediction of flow features, including onset of instability, was presented. The influence of bubble size on transition from low-Reynolds number bubbly flow to slug flow in a vertical pipe was experimentally described [1013]. The effects of the inlet conditions were addressed. Forced convection boiling of steam and water in a vertical annulus at high qualities was measured [1014]. Some correlations were evaluated. Turbulent subcooled boiling in an annular channel was experimentally and numerically studied [1015]. Simultaneous measurements of velocity and temperature were taken and used to evaluate the turbulent Prandtl number. The heat/mass transfer analogy was considered for two-phase flows in narrow channels [1016]. Though the two share a requirement for accurate estimation of the thickness of the liquid film between confined bubbles and the channel wall, no useful analogy was found. A better model for low-pressure subcooled boiling was developed and put into RELAP5/MOD2 [1017]. A two-fluid model was tested for application to subcooled boiling in an annular channel [1018]. Some weaknesses were identified. A mechanism for hydrodynamically-controlled onset of significant voiding in microtubes was proposed [1019]. Important is the process of bubble departure from the walls. A CHF correlation was presented for subcooled boiling in narrow channels [1020]. Experimental results were used for modeling support. A conjugate analysis was applied to flow boiling in order to describe the non-uniformity of heating of the channel [1021]. A facility was described for measurements of three-dimensional, local subcooled flow boiling heat flux and CHF in plasma-facing walls [1022]. Measurements of bubble characteristics in subcooled flow boiling were made with digital imaging [1023]. A void fraction model was formulated.

Flow boiling in channels with cross-corrugated walls was investigated [1024] and convective boiling in a compact serrated plate-fin heat exchanger was experimentally evaluated [1025]. The heat exchanger flow was characteristic of slug flow rather than annular. CHF values were measured in a vertical, spirally-internally-ribbed tube under high-pressure conditions [1026]. Enhancement was demonstrated. Experiments documented forced convection boiling of fluorocarbon liquid in reduced size channels [1027]. One surface was with longitudinal microfins on the chip (heater). Heat transfer and flow patterns for two-phase flow of R-134a in horizontal smooth and microfin tubes were measured [1028]. Flow maps were developed. A new correlation of heat transfer coefficients was presented for evaporation of refrigerants in microfin tubes [1029]. Though simpler, the new correlation was shown to be more accurate than the existing correlations when applied against the chosen data set of 749 points. The effects of enhancement geometries on flow instabilities were experimentally evaluated [1030]. A comparison with bare tube performance was presented in terms of flow stability. Flow boiling with enhanced tubes having pores and connecting gaps was experimentally evaluated [1031]. The pore size for maximum heat transfer coefficient was dependent on fluid and enhancement geometry. The effects of flow obstructions in a vertical tube cooled with upward flow of R-134a were measured [1032]. Important were (1) the degree of flow blockage, (2) the obstruction shape, (3) the leading and training edge shapes and (4) the streamwise separation of flow obstructions. The onset of nucleate boiling and active nucleation site density were measured for subcooled boiling [1033]. Correlations for nucleation site density were given. Subcooled boiling modeling for low-pressure conditions for inclusion in thermal–hydraulic codes was addressed [1034]. Experimental data were used for verification. A model was developed for flow boiling in an annulus [1035]. The model was put into a commercial code and comparisons were made against data. A drift-flux model was developed for bubbly flow [1036]. Recommendations were given for using the results for modeling developing bubble flow. A model was presented for predicting one-component, critical, two-phase pipe flow [1037]. Data were taken and a correlation was developed for predicting interfacial heat transfer in subcooled flow boiling [1038]. Condensation heat transfer at the interface is time dependent. A non-equilibrium heat transfer model was presented for post-dryout, dispersed flow. Radiation was shown to be important [1039].

Experiments were conducted to study boiling mechanisms in all boiling regimes under steady-state and transition conditions [1040]. Boiling curves were different for transient heating versus steady-state conditions. Experiments were conduced to describe controlled cooling of a hot plate with a water jet [1041]. Transition from nucleate to film boiling was described.

An analysis was given for heat transfer and CHF of He II in a duct [1042]. Several vortices were generated around the heated surface. They were shown to have an important role in determining CHF. A prediction of CHF in He II was presented for flow through a channel having a step change in cross-sectional area [1043]. A two-fluid model and the theory of mutual friction were applied to predict CHF. Heat transfer measurements were made in forced convection flow of ammonia in a vertical tube for application to refrigeration units [1044]. A comparison was made of measured CHF values in horizontal and vertical tubes cooled with R-134a [1045]. An annular flow model was given for pure fluids and multicomponent mixtures [1046]. Comparisons were made against data. The inclusion of an entrained fraction correlation led to the best correlation. Flow boiling measurements were taken with *n*-heptane and with H_2O in microchannels of rectangular cross section [1047]. Measurements of boiling heat transfer of ternary mixtures at high qualities were taken [1048]. Local concentration non-equilibrium was taken into account in modeling the data. The influence of thermophysical properties on two-phase, enhanced-surface, channel flow boiling of refrigerants mixtures was presented [1049]. The effects of polarity on two-phase capillary tube flow were measured [1050]. Stronger polar fluids lead to much stronger disjoining pressures and evaporation is choked because liquid molecules on the vapor–liquid interface are strongly attracted by the solid wall. Boiling with binary mixed magnetic fluids was discussed [1051]. It was shown that heat transfer rates were improved by an applied magnet field when at the higher flow rates.

Visualization studies documented the effect of orientation of the surface on CHF [1052]. An interfacial lift-off model was modified and used to predict the orientation effect. Experiments were conducted to describe the effects of body force, surface tension force and inertial force on flow boiling CHF [1053]. Characteristics of the vapor layer were described. Numerical modeling of low-pressure subcooled boiling flows was discussed [1054]. It was shown that models developed for higher pressures may not be suitable for low-pressure predictions. Electrohydrodynamically (EHD) enhanced convective boiling of alternative refrigerants for application to smooth and enhanced tubes was discussed [1055]. A theoretical analysis determined the contributing terms of the EHD power consumption. Transient convective heat transfer coefficients of steam–water, two-phase flow in a helical tube under oscillatory flow conditions were measured [1056]. Correlations were proposed for steady and oscillatory flows. Equations for describing pressure wave propagation in bubbly fluids at very low void fractions were derived [1057]. In the ideal case, it was found that pressure waves damp to zero whereas the bubbles continue to oscillate but with the oscillations becoming incoherent. CHF in natural circulation boiling in vertical tubes was experimentally studied [1058]. The effects the oscillatory flow induced near CHF on CHF were discussed.

13.6. Two-phase thermohydrodynamic phenomena

A correlation was presented for heat and mass transfer on a porous sphere saturated with liquid and evaporating in a natural convection flow [1059]. Visualization was made of evaporation in capillary porous structures [1060]. A wire mesh was used as the porous wall geometry. Local dryout due to trapped bubbles leads to a decrease in heat transfer coefficient. An experimental study was made of evaporative heat transfer in sintered copper bi-dispersed wick structures [1061]. For the bi-dispersed wicks with the same small pore size, there exists an optimum large pore diameter that gives both the highest heat transfer coefficient and the highest CHF. A numerical study was conducted on heat transfer to homogeneous porous media [1062]. This is used in steam injection operations for an effective heating of porous media. A mechanism was presented for vaporization inside a microfin tube [1063]. The work defined the contributions made by nucleate boiling to the microfin tube evaporation performance. Liner stability analysis was applied to horizontal, two-phase flow with EHD extraction [1064]. The presence of the electric field promotes instabilities. An expression for critical Weber number was developed for toluene droplets dropping on the heated wall [1065]. A study of the spreading process was presented to find the conditions needed to get the droplets onto the heated surface. Experimental results were presented for flashing liquid jets in a highly expanded flow [1066]. Photography was used to describe the flashing process. Microscale explosive vaporization of water on an ultra-thin Pt wire was experimentally characterized [1067]. Important is the nucleation dynamics. The effects of polymer, surfactant and salt additives to the mitigation and suppression of vapor explosions were experimentally documented [1068]. The effect of capillarity on heat transfer at the interface was analyzed [1069]. The capillarity is helpful for increasing the condensation rate from vapor to liquid.

14. Change of phase—condensation

14.1. Modeling and analysis

Du and Wang [1070] modify the classical Nusselt theory and account for the effect of surface tension exerted by condensate film bending as well as the effect of shear stress on the vapor–liquid interface. El-Moghazy [1071] develops a simple model for heat transfer to horizontal low finned tubes by analyzing the region of thin condensate film where the tube is flooded. The effect of dust particles on the film flow in the initial region and on the intensity of heat and mass transfer is demonstrated for a vapor–gas mixture [1072]. A stratified flow model of film condensation in helically grooved microfin tubes has been proposed [1073]. The height of stratified condensate is estimated by extending the Taitel–Dukler model for smooth tubes, and assuming laminar film condensation on the surface exposed to the vapor flow, and an empirical equation for the lower part. An analytical study by Kliakhandler et al. [1074] indicates that heat conduction in the vapor phase becomes important as the condensate film becomes thick, and cannot be neglected as is usually done. An iterative condensation model for steam condensation is proposed that uses the heat and mass transfer analogy to account for the effects of high mass transfer, entrance effect, and interfacial waviness effect on condensation in the presence of a non-condensable gas in a vertical tube [1075]. A non-iterative model based on the iterative model is derived by assuming the same profile of the steam mass fraction as that of the gas temperature in the gas film boundary layer, and gives reasonable results.

Rose [1076] presents a semi-empirical model of film condensation on a horizontal wire-wrapped tube that accounts for capillary condensate retention between the wire and tube. The theoretical enhancement ratio depends only on the tube and wire diameters, wire pitch, surface tension and density of the condensate, and is independent of the vapour-to-surface temperature difference.

Condensate film distribution inside the cave-shaped cavity of a flat plate heat pipe is shown to depend on the mass flow rate and local velocity of the condensate [1077]. A homogeneous model approach is employed in the estimation of shear velocity, which is subsequently, made use of in predicting local convective condensation heat transfer coefficients inside a horizontal condenser tube [1078]. Downward flow over a horizontal tube is studied [1079], and a new singularity is identified on the rear part of the cylinder at the interface between the vapor stream and the condensate film in a region where very small velocities prevail in conjunction with vanishing shear rate. The effects of wavy geometry, the interfacial vapor shear and the pressure gradient on the local condensate film thickness and the heat transfer characteristics for mixed-convection film condensation with downward flowing vapors onto a finite-size horizontal wavy plate are studied numerically [1080]. An analytical model is presented for predicting film condensation of vapor flowing inside a vertical mini triangular channel [1081]. Due to surface tension effects in the corners, the axial variation of the average heat transfer coefficient inside an equilateral triangular channel is found to be substantially higher than that inside a round tube of the same hydraulic diameter in the entry region.

14.2. Global geometry

Belghazi et al. [1082] obtain data for tube bundles with surfaces enhanced using three-dimensional geometry (notched fins) and compare them with results for trapezoidal fins of different spacings. For the bundle and for a mixture of HFC23/HFC134a, inundation of the lowest tubes produces a significant reduction in heat transfer coefficient. A companion study [1083] studies film condensation for different surfaces: smooth surfaces, low trapezoidal fins (2-D) of varying pitch, and specific fins (3-D, C+ tubes) for HFC134a and a mixture of HFC134a/HFC23. Heat transfer to surfaces in pulsating condensing flows was studied [1084] for mean Reynolds numbers of 2600–4300, with instantaneous Reynolds numbers upto 18,000. The internal heat transfer is noted to increase by up to a factor of 1.8 due to the pulsating flow prior to the onset of condensation, and by up to 12 times after the onset of condensation.

14.3. EHD

Electrohydrodynamic (EHD) enhancement of heat transfer, commonly used for dielectric media used in refrigeration and heat pump devices, is less effective when applied to horizontal integral-fin tubes. The mechanism of EHD enhancement is discussed in [1085] and a new arrangement of the tube-electrode arrangement is proposed. A new set of correlations for EHD-enhanced condensation heat transfer is presented for condensation inside and outside smooth tubes oriented horizontally or vertically [1086]. EHD-enhanced in-tube condensation was studied for R-134a, the zeotropic mixture R-407c, and the near-azeotrope R-404a [1087]. All three refrigerants respond strongly to EHD enhancement, with R-134a having the most enhancement and R-407c showing the least.

14.4. Mixtures

A new model to predict the heat transfer coefficient and pressure drop for pure or blended halogenated refrigerants condensing in smooth tubes is presented [1088]. Predictions are compared with data for several refrigerants, and show excellent agreement. Another study examines the effect of non-condensable gases on direct-contact condensation heat transfer using the RELAP5/MOD3.2 code for horizontally stratified flow [1089]. In-tube condensation heat transfer coefficients are presented for the zeotropic refrigerant mixture R-22/R-142b for the case of smooth tubes [1090] and for microfin, high-fin, and twisted-tape insert tubes [1091].

14.5. Dropwise condensation

Several papers address the mechanism of dropwise condensation. Ganzevles [1092] use time-averaging with instantaneous infrared temperature measurements to quantify the thermal resistance of the condensate. They find that mixing and convection in the condensate reduces the resistance by a factor of 4 compared to purely conductive heat transfer. Kalman and Mori [1093] present experimental data on a single vapor bubble condensing in a subcooled liquid. The effects of processing conditions of polymer film on the dropwise condensation of steam on a surface coated with the polymer are investigated. Results indicate that depending on the surface treatment and the substrate, polytetrafluoroethylene (PTFE) films can give a 15-fold difference in condensation heat transfer enhancement over film condensation. Wayner [1094] performs detailed measurements of the droplet nucleation, growth and transfer of liquid from a drop to a corner meniscus. Interferometry is used to measure the liquid thickness profile and contact angle, which are related to the capillary pressure and spreading coefficient. It is found that small interfacial temperature differences of the order of 10^{-4} K can generate large differences in the free energy per unit volume, and significant affect transport processes. A companion study [1095] examines the slow growth characteristics of a condensing ethanol drop on quartz. Interferometry is used to obtain the transient liquid profile (curvature) and hence the pressure field. While the radius of curvature increased linearly with time, the contact angle was observed to remain constant at a constant condensation heat flux. Curvature, contact angle, interfacial subcooling, spreading velocity and adsorption are coupled at the contact line. Yamali and Merte [1096] propose a theory of dropwise condensation at large subcooling, including the effects of sweeping of departing drops.

14.6. Surface geometry

The effect of fin geometry was studied for condensation of downward-flowing HFC134a in a staggered bundle of horizontal finned tubes [1097]. In most cases, the highest performance was obtained by the tube with a three-dimensional structure at the tip of low fins. Kumar et al. [1098] study the relative performance of plain tubes, circular, splined, and partially splined circular integral-fin tubes for film condensation of steam and R-134a on horizontal tubes. The splined integral-fin tubes were found to give the best performance. The effects of fin height and helix angle were documented for three types of herringbone microfin tubes and compared with a helical microfin tube and a smooth tube [1099]. A study on millimeter-scale rectangular channels indicates that existing correlations overpredict in-tube condensation heat transfer for such ducts and that liquid drawn into the corners alters the phase distribution in the annular flow regime besides stabilizing the annular regime at low flow velocities [1100].

15. Change of phase—melting and freezing

This is the change of phase (freezing and melting) section of the review. It is broken into several subsections including: melting and freezing of spheres, cylinders and slabs; Stefan problems; ice formation/melting; melting and melt flows; powders, films, emulsions and particles in a melt; glass technology; welding; energy storage—PCMs; casting, moulding, and extrusion; mushy zone—dendritic growth; solidification; crystal growth; droplets, spray and splat cooling; oceanic, geological, and astronomical phase change.

15.1. Melting and freezing of sphere, cylinders and slabs

In this subsection work was presented on phase change in radial models. These included the effect of length scales on microwave thawing dynamics in two-dimensional cylinders [1101]; heat transfer characteristics of melting ice spheres under forced and mixed convection [1102]; and the thermal effect of surface tension on the inward solidification of spheres [1103].

15.2. Stefan problems, analytical solutions/special solutions

Work in this subsection included evaluation of moving boundary problems from melting and freezing to drying and frying of food [1104]; an exponential heat balance integral method [1105]; and a network simulation method for solving phase-change heat transfer problems with variable thermal properties [1106].

15.3. Ice formation/melting

Work in this subsection included evaluation of ice formation due to direct contact heat transfer and sublimation [1107]; thermal characteristics of ice under constant heat flux and melt [1108]; ice melting by natural convection [1109] and in water and salt solutions [1110]; ice formation by cooling water-oil emulsion with stirring in a vessel [1111]. Further work on scale formation of ice from electrolyte solutions on a scraped surface heat exchanger plate [1112] and cool thermal discharge by melting ice and producing chilled air [1113] was also presented.

15.4. Melting and melt flows

This subsection of work includes a numerical study of steady flow and temperature fields within a melt spinning puddle [1114]; mass transfer at the interface during laminar melt flow [1115]; shape-factor effect on melting in an elliptic capsule [1116]; evaluation of shell thicknesses of iron graphite nodules after laser surface remelting [1117]; simulation of polyester high-speed thermal channel spinning [1118]; iron flow and heat transfer in a blast furnace hearth [1119]; transport phenomena in laser surface alloying with distributed species mass source [1120]; adaptive grid generation and migration for phase-change materials processes [1121]; molecular dynamics simulation of heat transfer and phase change during laser material interaction [1122]; and contact melting inside an elastic capsule [1123].

A subset of this work evaluated melting applications relevant to nuclear technology. These included an estimate of the crust thickness on the surface of a thermally convecting liquid–metal pool [1124]; characterization of heat transfer processes in a melt pool convection and vessel-creep experiment [1125]; and simulation of free-surface melt flows with application to corium spreading in the EPR [1126].

15.5. Powders, films, emulsions, polymers and particles in a melt

This subsection included work on modeling of femtosecond laser-induced non-equilibrium deformation in metal films [1127]; an inverse heat transfer problem for restoring the temperature field in a polymer melt flow through a narrow channel [1128]; creeping flow of a polymeric liquid passing over a transverse slot with viscous dissipation [1129]; and opposed-flow ignition and flame spread over melting polymers with gas flow [1130].

15.6. Glass technology

Recent advances in mathematical modeling of flow and heat transfer phenomena in glass furnaces was presented [1131].

15.7. Welding

This subsection included work on scaling analysis of momentum and energy in gas tungsten arc weld pools [1132]; resistance welding for thermoplastic composites [1133]; resistance spot welding of aluminium with spherical tip electrodes [1134]; effect of thermal convection in the subsurface molten layer on weld thickness [1135]; laser keyhole welding issues including role of recoil pressure, multiple reflections, and free surface evolution [1136]; the influence of fluid flow phenomena on the laser beam welding process [1137]; three-dimensional transient finite element analysis of heat transfer in stainless steel (304) pulsed GTA weldments [1138]; importance of Marangoni convection in laser full-penetration welding [1139]; and three-dimensional modelling of heat transfer and fluid flow in laser full-penetration welding [1140].

15.8. Energy storage—phase change materials (PCM)

Work in this area included evaluation of melting processes in PCM in the presence of a magnetic field in low-gravity environment [1141]; evaluation of capric and lauric acid mixture as latent heat energy storage for a cooling system [1142]; thermal and heat transfer characteristics of lauric acid in a latent heat energy storage system [1143]; investigation of carbon-fiber brushes on conductive heat transfer in phase change materials [1144]; crystal growth rate in disodium hydrogenphosphate dodecahydrate [1145]; producing chilled air in cool thermal discharge systems with air flowing over an ice surface by complete removal of melt [1146]; effect of ultrasonic vibrations on phase-change heat transfer [1147]; and analysis of solid–liquid phase change heat transfer enhancement [1148].

15.9. Casting, moulding and extrusion

Work in the casting area included evaluation of macroexothermic phenomena during casting [1149]; control of heat transfer and growth uniformity of solidifying copper shells [1150]; mould evaluation for high speed continuous casting of steel billets [1151]; microstructure simulation of aluminum alloy using parallel computing technique [1152]; particle distribution in cast metal matrix composites [1153]; evaluation of fluid flow, heat transfer and solidification in the bending-type square billet continuous casting process [1154]; numerical simulation of squeeze cast magnesium alloy AZ91D [1155]; texture enhancement by inoculation during casting of ferritic stainless steel strip [1156]; outlet positions and turbulence mixing in a single and multi strand tundish [1157]; effect of outlet positions, pouring box, and shroud immersion depth on mixing in a caster tundish [1158]; and analysis of coupled turbulent flow and solidification in the wedge-shaped pool with different nozzles during twin-roll strip casting [1159].

Additional work on interfacial heat transfer resistances and characterization of strip microstructures for Al–Mg alloys cast on a single belt casting simulator [1160]; evaluation of the film casting process [1161]; gap distance effects on the cooling behavior and the microstructure of indirect squeeze cast and gravity die cast 5083 wrought Al alloy [1162]; porosity formation in direct chill cast aluminum–magnesium alloys [1163]; evaluation of the effect of vacuum on mold filling in the magnesium EPC process [1164]; evaluation of molten flux layer thickness profiles in compact strip process moulds for continuous thin slab casting [1165]; modelling of thermal stratification phenomena in steel ladles [1166]; effect of vibration on casting surface finish [1167]; fluid flow and heat transfer in twin-roll casting of aluminum alloys [1168]; filling and solidification of permanent mold castings [1169]; cooling rate evaluation for bulk amorphous alloys from eutectic microstructures in casting processes [1170]; mass and heat transfer during feeding of castings [1171]; chill casting of aluminum alloys for industrial scale ingots [1172]; melt flow, heat transfer and non-equilibrium solidification in planar flow casting [1173]; mold filling and solidification processes under pressure [1174]; and prediction of thickness of mould flux film in continuous casting mould [1175].

In addition, modeling of heat transfer and deformation in film blowing process [1176] as well as simulation of non-isothermal melt densification of polyethylene in rotational molding [1177] were presented.

15.10. Mushy zone—dendritic growth

Work in this area includes average momentum equation for interdendritic flow in a solidifying columnar mushy zone [1178]; adaptive phase field simulation of dendritic growth in a forced flow at low supercooling [1179]; concentration fields in the solidification processing of metal matrix composites [1180]; numerical simulation of initial microstructure evolution of Fe–C alloys using a phase-field model [1181]; two-phase mushy zone during freeze coating on a continuous moving plate [1182]; sharp-interface simulation of dendritic solidification of solutions [1183,1184]; mushy zone equilibrium solidification of a semitransparent layer subject to radiative and convective cooling [1185]; and a fixed-grid finite element based enthalpy formulation for generalized phase change problems with mushy regions [1186].

15.11. Solidification

Work in this subsection included scaling analysis of momentum, heat, and mass transfer in binary alloy solidification problems [1187]; solidification and residual stress in the GMAW process for AISI 304 stainless steel [1188]; a control volume method for solidification modelling with mass transport [1189] and domains subjected to viscoplastic deformation [1190]; computational model for solutal convection during directional solidification [1191]; a numerical study of solidification in the presence of a free surface under microgravity conditions [1192]; a macro/micro model for magnetic stirring and microstructure formation during solidification [1193]; microsolidification process in multicomponent system [1194]; a numerical study of anisotropy and convection during solidification [1195]; linear stability analysis of the solidification of a supercooled liquid in a half-space [1196]; boundary element model of microsegregation during volumetric solidification of a binary alloy [1197]; evaluation of the heat transfer coefficient during the solidification of aluminum [1198] and during solidification of cast iron in sand mould [1199]; heat transfer at the metal/substrate interface during solidification of Pb–Sn solder alloys [1200]; and evolution of convection pattern during the solidification process of a binary mixture: effect of initial solutal concentration [1201].

Additional work included work on an inverse convection–diffusion problem of estimating boundary velocity [1202]; simulation of solidification processes in enclosures [1203]; solidified layer growth and decay characteristics during freeze coating of binary substance [1204]; numerical evaluation of heat transfer, fluid flow, and stress analysis in phase-change problems [1205]; a computational study of binary alloy solidification in the MEPHISTO experiment [1206]; an analytical self-consistent determination of a bubble with a deformed cap trapped in solid during solidification [1207]; multiscale computational heat transfer with moving solidification boundaries [1208].

15.12. Crystal growth

Crystal growth work includes both general work as well as more specialized Bridgman, Czochralksi and epitaxial studies. The general work included evaluation of optical heating for controlled crystal growth [1209]; experimental modeling of mass crystallization processes in the volume of a flat magma chamber [1210]; a method to study polymer crystallization during processing [1211]; magnetic field suppression of melt flow in crystal growth [1212]; direct numerical simulation of solid-layer crystallization from binary melt [1213]; effects of crystal growth rate and heat and mass transfer on solute distribution [1214]; identification of furnace thermal characteristics from resistance measurements [1215]; development of a method to control directed semiconductor crystallization in space [1216]; transverse thermal effects in directional solidification [1217]; convective effects during diffusivity measurements in liquids with an applied magnetic field [1218]; an estimation of purity and yield in purification of crystalline layers by sweating operations [1219]; experimental verification of the numerical model for a CaF_2 crystal growth process [1220]; a global thermal analysis of multizone resistance furnaces with specular and diffuse samples [1221]; analysis of secondary radiation (multiple reflections) in monoellipsoidal mirror furnaces [1222]; and solutocapillary convection in the float-zone process with a strong magnetic field [1223].

Bridgman crystal growth work included evaluation of G-jitter effects during directional solidification [1224] and within magnetic fields [1225]; axial and radial segregation due to the thermo-convection in the semiconductor crystals grown in a low gravity environment [1226]; evaluation of factors affecting isotherm shape of semi-transparent BaF_2 crystals [1227]; investigation of the Bridgman growth of a transparent material [1228]; solidification thermal parameters affecting the columnar-to-equiaxed transition [1229]; temperature oscillations on the interface velocity [1230]; evaluation of growth of semiconductor crystals under microgravity [1231]; and spoke pattern evaluation in Bridgman top seeding convection [1232].

Work on Czochralski method of crystal growth includes global analysis of heat transfer in growing BGO crystals ($Bi_4Ge_3O_{12}$) [1233]; heat and oxygen transfer in silicon melt in an electromagnetic Czochralski system [1234]; radial distribution of temperature gradients in growing CZ–Si crystals and its application to the prediction of microdefect distribution [1235]; effect of internal radiation on thermal stress fields in CZ oxide crystals [1236]; global simulation of a silicon Czochralski furnace [1237]; dopant segregation during liquid-encapsulated Czochralski crystal growth in a steady axial magnetic field [1238]; coupling of conductive, convective and radiative heat transfer in Czochralski crystal growth process [1239]; a volume radiation heat transfer model for Czochralski crystal growth processes [1240]; computer simulation of point-defect fields and microdefect patterns in Czochralski-grown Si crystals [1241]; buoyant-thermocapillary and pure thermocapillary convective instabilities in Czochralski systems [1242]; and magnetic stabilization of the buoyant convection in the liquid-encapsulated Czochralski process [1243].

Epitaxial crystal growth work included evaluation of applied magnetic field on flow structures in liquid phase electroepitaxy [1244] and epitaxial growth of 4H SiC in a vertical hot-wall CVD reactor [1245].

15.13. Droplets, spray and splat cooling

Work in this subsection included metal droplet deposition on non-flat surfaces: effect of substrate morphology [1246]; presolidification heat transfer and fluid dynamics in molten microdroplet deposition [1247]; transport and solidification phenomena in molten microdroplet pileup [1248]; single fluid atomization through the application of impulses to a melt [1249]; multiphase flow with impinging droplets and airstream interaction at a moving gas/solid interface [1250]; modeling of droplet impact and solidification [1251]; splat shapes in a thermal spray coating process [1252]; splashing of molten tin droplets on a rough steel surface [1253]; evaluation of spray cooling for the continuous casting of multi-component steel [1254]; interfacial heat transfer during cooling and solidification of molten metal droplets impacting on a metallic substrate [1255]; heat transfer analysis of impulse atomization [1256]; solidification study of aluminum alloys using impulse atomization [1257]; solidification modeling of plasma sprayed TBC [1258]; and an integrated model for interaction between melt flow and non-equilibrium solidification in thermal spraying [1259].

15.14. Oceanic, geological, and astronomical phase change

This last subsection work included effects of repetitive emplacement of basaltic intrusions on thermal evolution and melt generation in the crust [1260]; modeling of crustal scale convection and partial melting beneath the Altiplano-Puna plateau [1261]; analysis of anatectic migmatites from the roof of an ocean ridge magma chamber [1262]; study of thermal conditions in the THM growth of HgTe [1263]; impact hot spots on the cold surface of the early Earth [1264]; and some thermal constraints on crustal assimilation during fractionation of hydrous, mantle-derived magmas [1265]; and water/magma interaction [1266].

16. Radiation

The papers below are divided into subcategories that focus on the different impacts of radiation. Most of the papers report the results of modeling studies. Papers describing the development of new numerical methods themselves are reviewed in the numerical methods section under the subcategory radiation.

16.1. Radiative transfer calculations and influence of the geometry

Several methods have been used to study radiative transfer in one- or multi-dimensional systems. The discrete ordinate method (DOM) is popular among many authors. Guo and Kumar [1267] model the transient heat transfer in three dimensions using DOM. Li et al. [1268] introduce a new spherical surface symmetrical equal dividing scheme. The reduction of false scattering effects is discussed in [1269,1270]. Coelho [1271] also studies bounded high-order resolution schemes for the DOM. Dual mode heat transfer in cylinders is discussed in [1272].

Liu et al. use a discrete transfer method to investigate three-dimensional surface radiation [1273]. Inverse radiation analysis is applied in [1274,1275]. Garber and Tangerman model crystal growth as radiative transfer in closed axisymmetric chambers [1276]. An accelerated method to solve the P-1 equation is presented in [1277]. The cooling of glass is modeled in [1278] as a simplified diffusion type process.

Mulet et al. [1279] model radiative transfer between two semi-infinite bodies at a subwavelength scale. Resonant surface waves may enhance the heat transfer by orders of magnitude.

16.2. Radiation and combustion

Combustion problems involve radiative heat transfer as well as participating media, and other heat transfer modes.

A number of papers consider radiation in flames. Oxygen-enhanced flames are studied in [1280,1281]. Fourier transform infrared spectroscopy is used to study a diffusion flame in [1282]. The effects of gas and soot radiation on flames are considered in [1283–1285]. Shamim studies the effect of the Lewis number on radiative extinction [1286].

Small gas-fueled furnaces are modeled in [1287], fluidized bed combustors in [1288]. Reddy and Basu investigate the effect of CO_2 on radiative transfer in fluidized bed combustors [1289]. The radiative heat transfer related to fires and its influence on fire spread is discussed in [1290–1292].

The energy concentration in combustion waves is the topic of study [1293]. The heat and mass transfer in sodium pool combustion are modeled in [1294].

16.3. Radiation and small particles

A number of publications consider radiative heat transfer in systems involving small particles.

Liu et al. [1295] study transient radiation–conduction in semitransparent particles and the emissive power of particles with non-uniform temperature [1296]. Two-phase gas-particle media are considered in two-dimensional enclosures [1297], and their effect on the propagation of acoustic waves is studied in [1298]. Consalvi et al. [1299] discuss an averaging procedure for radiative transfer from particulate media, while Raun et al. [1300] propose a Monte Carlo approach. The effect of soot aggregation on the radiative properties in the infrared is studied in [1301]. The influence of radiation on the oxidation of small metal particles is investigated in [1302]. The propagation of a laser-driven shock wave in a gas-particulate medium is discussed in [1303]. Radiation from solid carbon particles is also found as important in the plume of an Atlas rocket [1304].

16.4. Participating media

Papers in this category focus on emission and absorption properties, as well as scattering properties of the participating medium.

Penner's article [1305] presents an overview of the author's 50 years of research on radiant heat transfer and the associated studies in quantitative spectroscopy. Several papers deal with the efficient description of radiative transfer in participating gaseous media. An exponential wide band model for transfer in one- and two-dimensional enclosures containing CO_2 and H_2O is presented in [1306]. A full-spectrum correlated-k distribution is applied to one-dimensional transfer in CO_2–N_2 and two-dimensional transfer in CO_2–H_2O–N_2 mixtures [1307]. The correlated-k distribution, spectral-line based weighted sum of gray gases, and weighted sum of gray gases method are compared for radiation from non-gray gases in three-dimensional enclosures [1308]. Goutiere et al. [1309] draw attention to the hybrid correlated-k/statistical narrow band method with band regrouping strategies. A new model for smooth absorption coefficients is discussed in [1310]. Reciprocal and forward Monte Carlo methods with a correlated-k approach are compared in [1311]. The full spectrum correlated-k distribution is applied to non-gray radiation of combustion gases in [1312]. A statistical narrow band model and ray-tracing is used to model radiation in cubic enclosures with real gases [1313]. Heragu et al. [1314] model the emission from engine exhaust and its incidence on a sensor using a narrow band model. The inverse radiation problem for a radiant cooler is solved in [1315] to estimate the heat-transfer coefficient in participating media.

Semitransparent media featuring absorption and emission and sometimes spatially non-uniform refraction are studied in several papers. Graded index semitransparent slabs with gray boundaries are considered in [1316] and sinusoidally varying indices of refraction are studied in [1317]. Infinite semitransparent cylinders are discussed in [1318]. The internal distribution of radiation absorption in one-dimensional media is investigated in [1319]. Two-dimensional semitransparent media are studied in [1320].

Isotropic scattering is important in several participating media. Non-Fourier conduction in the presence of isotropic scattering is studied in [1321]. Three-layer composites are studied in [1322,1323], semitransparent composite layers in [1324,1325]. Parallel ducts are modeled as porous medium in [1326]. A collapsed dimension method is used to study absorbing–emitting–scattering media inside one-dimensional gray enclosures [1327], two-dimensional media are discussed in [1328], three-dimensional media in [1329]. Sacadura and Baillis [1330] investigate dispersed media such as fibers, foams, and pigmented coatings. An equivalent Mueller matrix for a plane medium is derived in [1331]. Ref. [1332] investigates the scattering from polydisperse diesel droplets.

Several papers also deal with the influence of anisotropic scattering. Altac and coworkers apply a synthetic kernel method both to isotropic [1333,1334] and anisotropic scattering problems [1335,1336]. The discrete ordinate method in anisotropic scattering problems is studied in [1337,1338]. Absorption, emission, and anisotropic scattering in media in complex enclosures are discussed in [1339]. A zone method for radiation in anisotropically scattering media bounded by anisotropically reflecting walls is described in [1340]. A collapsed dimensions model is used to describe a one-dimensional participating medium in [1341]. Stochastic radiative transfer with isotropic and anisotropic scattering is also studied in [1342].

Various papers focus on numerical approaches to model participating media. A Monte Carlo model to predict the propagation of a collimated beam is described in [1343]. Ref. [1344] discusses wavelets and the discrete ordinate method for radiation in two-dimensional rectangular enclosures with non-gray media, and a radiation element method by ray emission model is introduced in [1345] for three-dimensional media and enclosures.

16.5. Combined heat transfer

Papers in this subcategory consider the combined effect of radiation with conduction and/or convection. An implicit finite difference method coupled to a ray tracing method is used to model conduction and radiation in semitransparent media [1346]. Transient conduction and radiation with variable thermal conductivity are discussed in [1347]. Spherical turbid media with anisotropic scattering are considered in [1348]. Conduction and radiation heat transfer in fibrous media are studied in [1349,1350]. Combined conduction and radiation also play a role in the rapid thermal processing of plasma display panels [1351]. Both effects also dominate the conventional, microwave, and combined heating of ovens [1352]. An uncommon paper in the context of this review deals with the radiative and conductive transfer in planetary regoliths of the Moon and Mercury [1353].

Combined convection and radiation are discussed in [1354] with respect to the flow of an incompressible viscous fluid past a moving vertical cylinder. Free convection in a square duct with specular reflection by an absorbing–emitting medium is studied in [1355]. Convection and radiation also play a role in the chemical vapor deposition of silicon [1356]. Both processes also determine the nanoscale heating of a sample with a probe [1357].

16.6. Intensely irradiated materials

Several papers deal with materials that are subjected to intense radiation. Ref. [1358] discusses time-resolved laser-induced incandescence as a method for sizing micronic carbonaceous particles. The influence of multiphoton absorption of 193 nm high-power, short-pulse excimer laser radiation on the heating of glass is discussed in [1359]. Ultrafast laser heating of metal films can be affected by microvoids [1360].

16.7. Experimental methods and systems

Only few studies of experimental methods and systems are reported this year. A multi-wavelength pyrometer–photometer has been developed to determine the temperature and concentrations of combustion products on the basis of the infrared self-radiation [1361]. Ref. [1362] describes a monochromatic-reference method to obtain 3D temperature images of large-scale furnaces. Extensive experimental studies of the heat transfer processes in an oven-like enclosure are reported in [1363]. A Monte Carlo model to facilitate radiometric temperature measurements in silicon wafer rapid thermal processing furnaces is discussed in [1364]. Air radiation measurements behind a strong shock wave are reported in [1365].

17. Numerical methods

One of the breakthroughs of the last century is the ability to simulate physical processes on a computer. The simulation of heat transfer, fluid flow, and related processes is made possible by numerical solution of the governing partial differential equations. The numerical simulation is used in academic research and in industrial applications. In this review, the papers that mainly focus on the *application* of numerical methods to particular problems are reviewed in the appropriate application category. The papers that primarily deal with the development of a numerical technique are included in this section.

17.1. Heat conduction

A Green's function approach is presented for steady-state heat conduction in a rectangular parallelepiped [1366]. An algorithm is described to solve the sensitivity equations in transient heat conduction [1367]. A posteriori error estimate technique is constructed for heat conduction on unstructured triangular meshes; an equal distribution of error on all triangles leads to an adaptive mesh refinement procedure [1368]. The method of second moments is used for computational heat transfer [1369]. A simple procedure is described for thermal response factors and conduction transfer functions [1370]. A spectral method is developed for conduction through a multilayer multiblock case [1371]. A flux-splitting algorithm is used for non-Fourier heat conduction [1372].

The transfer matrix method is employed for the solution of periodic heating problems [1373]. An approximate analytic method is described for dual-phase-lagging heat transport equations [1374]. A two-temperature model is presented for ultrashort laser pulse interaction with a metal film [1375]. An operator-splitting, radial-basis-function method is developed for the solution of transient Poisson problems [1376].

A general method is presented for the direct determination of the shape of a body that achieves specified design criteria; although the method is general, it is demonstrated for heat conduction problems [1377].

17.2. Inverse problems

A maximum entropy method is used for the solution of inverse heat conduction [1378]. Thermal contact resistance between rough surfaces is determined by the application of inverse analysis [1379]. Thermophysical properties of super-hard synthetic materials are derived by employing the inverse heat conduction approach [1380]. Singular value decomposition and model reduction are used for inverse heat conduction problems with temperature data that contain significant noise [1381]. A generalized optimum dynamic filtration method is presented for solving inverse heat transfer problems [1382]. An inverse solution technique is used for estimating interface conduction between periodically contacting surfaces [1383]. A combination of the Laplace transform and a finite-difference method is proposed for the prediction of boundary conditions in an inverse heat conduction problem [1384]. An inverse technique is based on the identification of multiple heat sources [1385].

17.3. Fluid flow

The progress and challenges in high-performance computing in computational fluid dynamics are reviewed; the main challenge is identified as the understanding of turbulence and its effect on engineering applications [1386]. A general continuous sensitivity formulation is presented for complex flows [1387]. The Richardson extrapolation technique is evaluated for two-dimensional laminar and turbulent flow problems; the technique is shown to be unsatisfactory for the problems investigated [1388]. A post-processing tool is developed for the verification of finite-volume computations [1389]. A meshless formulation is presented for three-dimensional viscous flow [1390].

A parallel algorithm using loosely coupled computers is described for the efficient solution of the pressure-correction equation for incompressible flows [1391]. A unified parallel numerical method is presented for flows of all regimes including incompressible and supersonic flows [1392].

17.4. Pressure-correction techniques

Several flow calculation methods originate from the SIMPLE procedure and employ a pressure-correction equation derived from the mass conservation principle. A comparative evaluation is made of seven methods based on the pressure-correction equation for incompressible *multiphase* flows [1393]. The special features of pressure-correction equations and their effect on the overall flow solution are systematically investigated [1394]. A dual-dissipation scheme is proposed for the treatment of the pressure–velocity coupling in non-orthogonal colocated grids [1395]. The Nonstaggered APPLE algorithm is described for incompressible flows in curvilinear coordinates [1396]. Different practices are discussed for the interpolation of velocity components to obtain the interface velocity in a colocated grid system [1397]. A pressure-based finite-volume method is formulated for unstructured grids and applied to laminar reacting flows [1398].

17.5. Additional flow solution techniques

A calculation procedure is described for complex time-dependent geometries; it employs a moving mesh and applies the space conservation law [1399]. A local block refinement procedure is used in conjunction with a multigrid flow solver [1400]. An equal-order finite-element method is developed for natural convection in complex domains [1401]. A robust scheme based on the artificial compressibility concept is presented for viscous incompressible flow [1402]. An auto-adaptive finite-element method is described for the Navier–Stokes equations [1403].

17.6. Free surface flows

A new method is presented for the treatment of the free surface between a non-spherical bubble and the surrounding liquid [1404]. The volume-of-fluid method is applied to the buoyancy-driven flow of bubbles in a liquid [1405]. A finite-element method is adapted to free-surface flows with surface tension [1406]. A direct-predictor method is proposed for the prediction of a steady terminal shape of a bubble rising through quiescent liquid [1407]. Heat and mass transfer at the surface of a gas bubble is calculated by a numerical procedure [1408]. The free-surface flow of a liquid in a printing process is simulated by a problem-specific meshing strategy [1409].

17.7. Turbulent flow

Whereas the "k-epsilon" turbulence model is widely used, the specification of epsilon at an inlet boundary is often arbitrary. Results from direct numerical simulation (DNS) of turbulence are used to determine accurate values of epsilon and a procedure for the specification of epsilon is proposed [1410]. Reynolds averaged predictions of turbulent flow in a turbine passage are presented to illustrate the shortcomings of common turbulence models; certain constraints are proposed for improving the predictions [1411]. Exact renormalization is used to provide an estimate of turbulent eddy diffusivity [1412]. Scalar turbulent dispersion from a line heat source is studied for moderate and high Prandtl number fluids [1413].

17.8. Other studies

A spectral algorithm is used to calculate flows in microchannels under the influence of pressure gradients and electro-osmotic forces [1414]. An exponential function is embedded in a two-boundary grid generation technique for turbulent heat transfer in a piston-cylinder system [1415]. A number of features such as turbulent spray computation, probability density function, unstructured grids, and parallel computing are combined to predict the fluid dynamics of sprays with chemistry/turbulence interaction [1416]. An efficient algorithm is presented for locating particles within arbitrary unstructured grids [1417]. A moving mesh is used for the simulation of helium expansion and thermal–hydraulic behavior in superconducting magnets [1418,1419]. A posteriori adaptive mesh refinement method is applied to a three-dimensional convection-diffusion problem [1420].

18. Properties

Considerable effort has been directed toward the investigation of thermal conductivity and diffusivity values for composites, sub-micro–nano meter systems and other specialized applications.

18.1. Thermal conductivity and diffusivity

Experimental works include photoacoustic technique studies of buried multilayered systems, curing temperature variation of thick glass, epoxy composite laminates and imagining of micrometer and sub-micrometer size surface variations using a scanning thermal microscope (SThM) [1421–1423]. Other papers report results for amorphous silicon thin films, silicon and germanium properties measured with the hot-wire method, and thermal property variation of aluminosilicate fiber radius [1424–1426]. A series of papers include results for laser-sprayed coatings, effect of crystal order on properties, liquid aromatic hydrocarbon thermal properties, phenolic foam insulation, compressed wood, and ground beef patties under infrared radiation [1427–1433].

Analytical works feature the role of structure influence on thermal properties: A packing algorithm for complex shapes, interface and strain effects, nanowire size, network structure for epoxy resin–carbon black composites as well as EPOM rubber Ti ceramic composites. [1434–1438]. Yet other papers consider thin, solid non-conducting layers, glass foams, bidispersed porous media and the cubic cell soil model [1439–1442].

18.2. Heat capacity

Investigations in this and related properties embrace a variety of systems and modes of study. Thus thermal characteristics of materials with a nanometer scale are reported for a narrow wire as well as the associated interface. Nanophase separation was studied in diblock and triblock copolymers using the heat capacity. Using a double twin micro calorimeter sorption isotherms and enthalpies are determined for vapors or water, ethanol and other liquids. Flow densimetry and flow microcalorimetry are employed to study the effect of electrolytes, surfactants and alcohols on polystyrene latexes [1443–1446]. Other papers focus on micelle formation by surfactants, Henry's law constants of chlorinated ethylenes in alcohol solution, temperature dependence of gas–liquid chromatographic retention and the heat capacity of an ideal gas along an elliptical PV cycle [1447–1450].

18.3. Miscellaneous systems and investigative procedures

Calorimetric measurements are reported for batch cultures of *Bacillus Sphaericus* 1593M, characterizing resin cure in thermosetting composities, and a thermal gravimetrical apparatus used to determine solid-side mass diffusivity for a water vapor-silica gel system [1451–1454]. Radiative properties (spectral) are identified for polyurethane foam and Planck mean absorption coefficients for HBr, HCl and HF and shock experiments with porous Ni samples explore near critical point behavior [1455–1458]. For bi-dispersed porous media a fractal permeability model is developed, cellular metal structures characterized using ultrasonics, a new method of melt spinning using grooved and ceramic chill rolls to manufacture magnetic substances is described and the possibility of managing soil physical properties for environmental protection presented [1459–1462].

19. Heat exchangers and thermosyphons

Applications: The extraordinary range of heat transfer applications is indicated by a group of papers which treats: rotating heat exchangers, commercial blood oxygenerators, thermoacoustic and thermoelectric devices, space craft radiators, pressurized bubble columns, and soil and deep bore heat exchangers [1463–1471].

19.1. Heat exchangers

Design modeling, optimization, and performance are emphasized in studies focused on: a parallel flow exchanger, exchanger response to data uncertainties, counter current flow with variable properties, Nusselt number predictions for chaotic pipe flow, laminar counter flow concentric exchangers, active cavity effect on fluid dynamic behavior in exchangers, and the thermodynamic significance of local volume averaged temperature [1472–1479]. Other investigations continue to examine such matters: finite element solution of conjugate heat transfer, a hyperbolic dispersion model, the uniformity principle of temperature difference field, numerical simulations of thermal control, the constructal route to the design of a two-stream exchanger with maximum heat transfer per unit volume and a new steady-state formulation of temperatures along a double-pipe exchanger in counter flow when mass flow rate undergoes a step change [1480–1485]. Also considered are: identifying the quench front temperature in an infinite slab when rewetted, the use of a filtering technique to solve the problem of random uncertainties in temperature measurements, two-fluid porous media method for transient two-phase flow in complex geometries, and forced convection heat transfer in tube banks in cross flow [1486–1489]. Experimental works embrace a variety of systems and operating conditions: brazed aluminum exchangers under dehumidifying circumstances, overall heat transfer for combustion cases in elliptical tube exchangers, effect of layer depth on mixing in a diffusive two-layer system, steam condensation in a rectangular, horizontal channel, and radio tracer investigation of inadequate reactor heat transfer [1490–1494].

Plate heat changers are studied from a number of viewpoints: design of multi-stream types, heat transfer and pressure drop when used with ice slurries, numerical analysis under forced convection, screening for optimal configuration selection, effect of flow distribution to channels on performance, an algorithm for steady-state simulation, rating calculation of effectiveness from existing performance data and tests of air–water flow and heat transfer [1495–1502].

Additional efforts consider aspects of heat exchanger networks using different exchanger types, simulation, retrofit, behavior and general solution [1503–1507]. Flat tube exchangers, packed bed and fluidized exchangers with solid particle circulation and recycle effects are also taken up [1508–1515].

19.2. Augmentation and enhancement of heat transfer

Techniques for facilitating heat transfer continue to be reported in impressive number. The extension of heat transfer surface by fins is especially popular. A fin-tube exchanger is investigated using liquid crystal techniques, a plate finned tube exchanger by infrared thermography, measurements of performance are reported for a tube finned surface and annular fins of varying profile with variable heat transfer coefficient. Wavy finned surfaces employed with humid air flows are studied and the use of hydrophilic coating reported. Further papers report: performance of extruded-serrated and extruded-finned tube bundles, film condensation on horizontal low finned tubes, transient conduction in a fin-wall assembly, and the characteristics of a multi-pass heat exchanger similar to that used to melt snow [1516–1526]. Additional papers discuss circular tubes with internal longitudinal fins with tapered lateral profiles and aspects of multi-louvered fin geometry [1527–1530].

A significant effort has been directed toward vortex generation as a method of enhancing heat transfer: in a channel with built in oval tube, in a plain-fin-and-tube exchanger, for fin-tube bundles, inline fin-tube configuration, and flat tube bank with four vortex generators per tube [1531–1537]. Geometrical features also can affect heat transfer as found with triangular capillary grooves, threaded surface in vertical narrow channels, spiral wound membrane modules, wire-pm-tube exchangers, herringbone wavy fin-and-tube devices, corrugated wall exchangers, combination of spirally corrugated tubes with twisted tape, rounded cross wavy ducts, serpentine flow in baffled flow in parallel plate cell channels, and the snail entrance in a concentric exchanger [1538–1547]. Compact exchangers are optimized through flow visualization, boiling enhanced in a compact tube bundle, and a novel groove-shaped screen-wick miniature heat pipe described, and the Leveque equation generalized for use in cross corrugated channels of plat heat exchanger and other systems [1548–1551]. Heat transfer enhancement techniques can also play a role in energy conservation [1552,1553].

19.3. Compact, miniature, mini and micro exchangers

The miniaturization of heat transfer devices continues to spread to a growing number of applications: electronics cooling, micro heat pipes, wire-bonded micro heat-pipe arrays, microturbine recuperators, evaporation and boiling in microfin tubes, modelling of microchannel flows pressure drop in miniature helical channels, and microscale temperature measurements at an evaporating liquid surface [1554–1563]. For compact exchangers their importance in spreading heat pump use is studied, they begin to replace shell-an-tube exchangers in exchanger networks, and using minichannel flow passages appear as compact evaporators. Allowance is made for fouling in design of compact exchangers and reflux condensation in small scale passages reported [1564–1568].

19.4. Evaporators and condensers

Cooling towers are the subject of a number of papers: Evaporative cooling of water by natural draft, thermal-hydraulic performance for such devices, the use of thermal-fluid dynamic efficiency in towers and the reverse use of towers in sub-tropical regions for service hot water [1569–1572]. Other works to consider: spray column direct contact exchangers, the influence of thermal irreversibilities on diabatic distillation column performance, capillary-assisted water evaporators for vapor-absorption systems, modelling climbing-falling-film plate evaporators, evaporation-combustion affects in porous regenerator, investigation of the evaporating film of a molecular evaporator, and two-phase thermal analysis of evaporators [1573–1579]. Brazed aluminum evaporators are analyzed for the effect of humidity on performance [1580,1581].

Design and modeling of condensers consider the influence of aerosol deposition on horizontal finned tubes in cross-flow and the hot-wall condensers of domestic refrigerators [1582,1583].

19.5. Fouling

A group of papers describe probes and schemes for measuring and monitoring and mitigating fouling. A probe is developed to monitor gas-side fouling in cross flow and fouling intensity in boilers; $CaCO_3$ fouling is studied with a microscopic imaging technique; electronic anti-fouling is perfected to mitigate mineral fouling in enhanced-tube exchangers; and polyacrylic acid used as an antiscaling agent [1584–1589]. Modelling and design assess fouling and incorporate such assessments into the exchanger design [1590–1593]. Further data on fouling is provided for internal helical-rib roughness tubes in a cooling water tower, fouling layer formation on an exchanger exposed to warm, humid, particulate-laden air, and French experience with fouling in steam generator tubes [1594–1596]. One study suggests that while fouling is to be avoided and mitigated in almost all instances, fouled steam generator tubes showed better boiling heat transfer performance than new, chemically cleaned tubes [1597].

19.6. Thermosyphons/heat pipes

This device continues to find application across a wide range of heat transfer problems from space radiators to the cooling of buildings. Miniature heat pipes of improved performance cool PC notebooks and high heat flux electronic components. Toroidal thermosyphons widely used in solar water systems, nuclear reactors and geothermal energy system, are the focus of several works [1598–1604]. Two-phase closed thermosyphons are modeled for electronics cooling, applied to water-saturated soil conditions and a boiling heat transfer system, and improved to perform low temperature heat transfer [1605–1608]. Further works study wickless network heat pipes in high heat flux spreading applications, evaporative three finger glass designs, and the enhancement of heat transfer in an air preheater using the binary working fluid triethylene glycol (TEG)–water mixture [1609–1611]. Oscillating and pulsating heat pipes are modeled, and experimentally investigated [1612–1615].

19.7. Power and reversed cycles

The influence of heat exchanger performance on power plant efficiency is reported in several papers. Fore-casting thermal performance for a plant using sea-water cooling subject to tidal effects, optimization procedure for maximizing total plant efficiency of the humid air turbine (HAT) cycle, thermodynamic performance for a magnetohydrodynamic (MHD) power plant with variable temperature heat reservoirs and the effect of heat transfer on thermoelectric generators reflect the scope of efforts in this area [1616–1621].

Reversed cycle papers embrace diverse interests: design of integrated refrigeration systems and absorption machines, and a variety of factors for heat pump based systems (novel mechanical ventilation heat recovery, CO_2 air conditioning, thermoeconomic considerations in optimum allocation of heat transfer, performance of R-22 alternative mixtures [1622–1627]. Other papers simulate heat transfer in a solid absorption refrigeration system, optimize a two-stage ejector plant, model refrigerant flow through capillary tube exchangers, simulate vapor-compression liquid chillers and evaluate a window room air conditioner with microchannel condensers [1628–1633]. A series of papers report on the performance of various refrigerants: R407C substituted for R22 in shell and tube exchanger, isobutene (R600a) as domestic refrigerant, condenser performance for R-22 and R-707C, ozone friendly R-410A in a vertical plate exchanger, water/zerotropic mixture in tube-in-tube condenser, and two-phase pressure drop of refrigerants in horizontal tubes [1634–1639].

20. Heat transfer—general applications

20.1. Fluidized beds

The relationship between the parameters of a fluidized bed and the heat transfer to a body immersed in it are described by Al-Busoul [1640]. Another paper [1641] on the same relationship models the fluidized bed as a medium consisting of a double-particle layer and an even porous layer, and shows that radiative heat transfer is significant. A blast furnace is simulated with the SIMPLE algorithm using a multi-fluid model in which all phases are treated as fluids [1642]. A correlation was developed for the heat transfer coefficient on wing walls and water walls of circulating fluidized bed boilers [1643]. LDA measurements are used to calculate particle kinetic stresses in circulating fluidized beds [1644]. A novel semi-confined porous radiant recirculated burner (PRRB) concept is presented that reduces losses due to open-flame combustion [1645]. The effect of latent heat of fusion on heat transfer in fluidized-bed coating of thin plates was studied by Leong [1646]. The effect of pressure and average suspension density on bed-to-wall heat transfer in a pressurized circulating bed was studied in [1647].

20.2. Food processing

A numerical analysis was done of temperature variability in cooled biscuits using the Monte Carlo method [1648]. Experiments using infrared and microwave radiation showed that infrared radiation may increase or decrease the amount of surface moisture on the food/porous medium depending on the medium properties [1649]. A one-dimensional model was developed, based on experiments, that described the cooking of beef patties using far-infrared radiation over a range of fat contents [1650,1651]. Models were developed for deep-fat frying of cassava [1652] and tortilla chips [1653]. Wang and Sun [1654] perform finite element analysis to compare the cooling of cooked meats under different environments offered by slow air, air blast and water immersion cooling units. Zitny et al. [1655] present a model that seeks to explain some surprising pressure and temperature variations observed during pressure baking of starchy foods.

20.3. Nuclear reactors

Several papers dealt with thermohydraulics of the cooling flow in nuclear reactors. Chung et al. [1656] present a new criterion for choked flow in the bubbly regime of two-phase flow, based on characteristic analysis of the hyperbolic equations arising out of a two-fluid model. A model for critical heat flux (CHF) for low flow rates in a small diameter tube that takes into account accident conditions, such as reflood transients, is presented by [1657]. The effects of inter-wrapper flow, in which cold sodium is provided in an upper plenum of reactor vessel and covers the reactor core outlet, on the core temperature distribution is studied numerically [1658]. Legradi and Aszodi [1659] present an analysis of the natural convection flow between the reactor pressure vessel and the cooling pond of the reactor in accident conditions. Flow characteristics, axial dispersion, power and temperature distribution in toroidal loop reactors are analysed [1660]. Nayak et al. [1661] consider the stability of a natural circulation pressure tube type boiling water reactor with respect to two types of density-wave instabilities. Other papers include: natural circulation characteristics of a marine reactor in rolling motion [1662], thermal analysis of plutonium storage containers [1663], effects of coolant injection into the reactor containment under pressure vessel failure conditions and escape of molten fuel into the containment [1664], and finite element modeling of non-linear steady-state three-dimensional heat transfer in nuclear fuel rods [1665].

20.4. Aerospace

A few papers dealt with heat transfer problems associated with reentry of a vehicle into the atmosphere: optimization of high-temperature multilayer insulation [1666], effects of surface catalysis on stagnation heat transfer for entry into a CO_2 atmosphere [1667], and design of a heat shield required to function as both an ablator and a structural component [1668].

20.5. Electronics cooling

Papers dealing with improved heat sinks for cooling electronic systems included those on: experimental data obtained for heat transfer to finned metal foam sinks [1669], optimization of single and double layer microchannel heat sinks performed using existing correlations [1670], a sink with spatially uniform temperatures in both streamwise and transverse directions [1671], and heat transfer enhancement from enclosed discrete components using pin-fin heat sinks [1672]. Ma and Peterson [1673] show that heat transfer can be considerably increased if the base of a heat sink is fabricated as a heat pipe, and that as the heat sink length increases, the effect of increased thermal conductivity reaches a predictable limit. Other approaches used to enhance heat transfer were: use of metallic solid–liquid phase change materials (PCM) inside cooling microchannels of semiconductor devices [1674], addition of microfabricated boiling-enhancement structures in heat spreaders [1675], active control of transient heat transfer loads through single-phase microfluidics [1676], and a new type of oscillating vortex generator in cooling channels [1677].

20.6. Buildings

A set of correlations are presented for use in the ESP-r simulation program for modeling convective heat transfer at internal building surfaces [1678]. The energy performance of single-pane windows for different kinds of glazing was investigated [1679]. The effects of moisture through precipitation, soil type, foundation insulation, water table depth, and freezing on the heat transfer from the building foundation are investigated for two types of foundations: a slab-on-grade type, and a basement [1680]. The Luikov equations for mass transfer are solved for temperature distribution in a room, with different thermophysical properties of the spruce walls as influenced by moisture, along with the effects of vapor diffusion [1681]. The effect of mass and insulation location on heating and cooling loads is analyzed in buildings with massive exterior envelope components for six characteristic wall configurations [1682]. Lorente and Bejan [1683] present an optimization procedure for arriving at the internal structure of a wall that maintains a given structural strength while maximizing the thermal resistance of the wall. The effects of edge insulation on the ground heat transfer from buildings is investigated [1684].

20.7. Gas turbines/fuel cells

Several papers dealt with heat transfer in gas turbine engines. Azad et al. [1685] experimentally show that different arrangements of squealer on turbine blade tips can significantly alter the flow and heat transfer distribution on the tip. Didier et al. [1686] present time-resolved heat transfer measurements that show the effect of passing wakes, and shock impingement on the leading edge. The data of Kumar and Kale [1687] indicate that for ceramic-coated turbine blades, uncertainty in heat transfer coefficient estimation does not significantly affect metal temperatures when radiative heat transfer is included in the analysis. The paper by Willenborg et al. [1688] shows that using a honeycomb facing in a stepped labyrinth seal significantly reduces heat transfer to the platform as opposed to a smooth facing.

Various SGS models have been used to simulate turbulent fluid flow and heat transfer in piston engines, and it was found that the Van Driest wall damping model matched best with experimental data [1689]. Two papers [1690,1691] model heat and mass transfer in the porous cathode of a proton exchange membrane fuel cell for various operating conditions and design parameters. Koh et al. [1692] infer from CFD analysis that heat transfer in a molten carbonate fuel cell stack is well characterized by a two-dimensional model along the axial and vertical coordinates rather than on the cell plane.

20.8. Geophysical studies

The formation of an exocontact thermal field of a magmatic intrusion is modelled as a spreading of a thermal source delta-function [1693], and the resulting solutions of the heat-transfer equation are correlated with diffusion, thermal and kinetic parameters of an exocontant zone of a magmatic body. Ice-shell thicknesses of a few kilometers and ocean depths of a few hundreds of kilometers are calculated for steady-state models of tidal dissipation in Europa's ice shell [1694]. Data from experiments and direct numerical simulation are compared for a stratified store entrainment process [1695]. Cooling rate profiles of rhyolitic samples in nitrogen and air are used to make predictions of temperature in volcanic eruption columns of Mono crater [1696]. Numerical simulation of heat and mass transfer from hot dry rock to flowing water in a circular fracture was conducted to estimate the concentration of the dissolved silica at a production well [1697]. Plate tectonics and data from global seismic tomography are used as input boundary conditions to simulate global mantle convection [1698].

20.9. Manufacturing and processing

Welding. Becker and Potente [1699] present data to be used for developing a model of temperature profiles in anisotropic polymers during laser transmission welding. A multiple reflection model has been developed [1700] based on the level set method and ray tracing technique to investigate the energy transfer from the laser to the workpiece for the case of a cavity. The effect of an externally applied longitudinal magnetic field on the liquid metal in an arc welding process has been investigated numerically [1701]. Mahrle and Schmidt [1702] numerically predict temperature and velocity distributions as well as weld pool geometry using a steady-state model for transport phenomena in the fusion zone of deep penetration laser beam welded joints. A three-dimensional transient model is developed for the single-pass laser alloying process that allows prediction of species concentration in the molten metal pool, as well as across the cross-section of the solid alloy [1703].

Casting. A three-dimensional inverse analysis is adopted to estimate the unknown conditions (heat source in the grinding zone, heat transfer coefficient) on the workpiece surface during a grinding process [1704]. Heat transfer experiments on enhancing heat transfer with a high pressure water jet impinging on the contact zone in creep feed grinding showed significant improvements in material removal rate [1705].

Drawing. A novel mass-balance free-surface location technique along with shear-thinning and viscoelastic flow models for melt material is used for evaluating annular wire-coating flows with pressure- and tube-tooling [1706]. Cheng and Jaluria [1707] investigate the thermal transport and flow in optical fiber drawing at high draw speeds in a cylindrical graphite furnace, including necking and the influence of furnace geometry. The effects of surface or volumetric radiative flux, emissive power, angle of incidence, and internal reflection on the temperature and degree of cure on graphite/epoxy and glass/epoxy cylinders are evaluated in [1708].

Rolling. A pressure-correction algorithm of a transient finite element form is applied to analyse the flow instabilities that arise during reverse-roller coating [1709]. Jaklic et al. [1710] show that the thin oxide scale that forms as a billet is transported from the furnace to the rolling mill significantly affects the temperature profile. The effects of heat of deformation, the work-roll temperature, the rolling speed, and the heat transfer coefficient between the work-roll and the metal are quantified in a study of the temperature profiles of slabs in hot rolling [1711].

Machining. A study finds that the cutting force is reduced, surface finish improved, and chip width is reduced when machining a workpiece with the use of high-pressure coolant [1712]. In light of recent research that shows that the heat transfer coefficient is periodic over a flexible vibrating body, the electrodynamic machining (EDM) process is evaluated afresh, and it is explained why EDM wires undergo thermal buckling at low axial transport speeds and a series of transport instabilities at high axial transport speeds [1713].

Forging. Chang and Bramley [1714] describe a determination of the heat transfer coefficient at the workpiece-die interface for the simple upsetting forging process. The heat transfer data obtained from quenching experiments on nickel superalloys used in aerospace applications are used to study the influence of non-uniform spray distributions on residual stress patterns [1715]. Models of the heat transfer in the hot pressing process of ceramic materials have been built theoretically and designs of hot pressing technology are made through the study of the temperature field in the ceramic blanks [1716]. The approach aims to improve the quality of predictions through more accurate evaluation of the input parameters in the simulation of the sheet reheat phase of the thermoforming process [1717].

21. Solar energy

Papers are broadly divided into solar radiation, low-temperature solar applications, buildings, and high-temperature solar applications. Papers on solar energy that do not focus on heat transfer, for example, papers on photovoltaics (except for those that deal with building integrated components), wind energy, architectual aspects of buildings, and control of space heating or cooling systems are not included.

21.1. Radiation

Many papers in this category present modified modeling approaches to evaluate or use measured solar data. Driesse [1718] tested a relationship developed by Suercke in 2000 between sunshine duration and radiation and found that it provides accurate average values. A neural network model that generates synthetic hourly irradiation is compared to other synthetic generation methods in [1719]. A bi-exponential probability density function is proposed for predicting clearness indices by Ibanez [1720]. Ineichen [1721] proposes a new formulation for the Linke turbidity coefficient. Muneer [1722] proposes a correction factor for calibration of the shadow band pyranometer based on an anisotropic sky-diffuse distribution theory. Yang [1723] presents a model to estimate global irradiance from upper-air humidity. Myers [1724] presents a method to more accurately calibrate pyranometer measurements using low thermal-offset radiometers.

21.2. Low temperature applications

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

21.3. Flat-plate and low-concentrating collectors

Solar air heaters of various geometries are considered in numerous papers. Bhagoria [1725] and Momin [1726] developed forced convection Nusselt number and friction factors for absorber plates with ribs. Numerical solutions for an absorber in a porous medium are presented in [1727]. Optical properties of porous medium that might be considered for solar air collectors are presented in [1728]. Khedari [1729] developed Nusselt and Reynolds–Rayleigh number correlations for free convection in an open ended rectangular channel. Yeh [1730] presents data and a model for a solar air heater with finned upper and lower flow channels. Several papers consider simplified methods to predict collector efficiency [1731–1734]. Li et al. [1735] consider a flat-plate collector in which the absorber is immersed in an absorbent bed to provide both heating and cooling.

Hybrid photovoltaic/solar thermal collectors continue to gain attention. Sanberg [1736] derives analytical expressions for velocity and temperature rise in air gaps behind vertically-mounted photovoltaic panels. Zondag [1737] compares transient and steady-state models for combined photovoltaic–thermal collectors. Tests of hybrid photovoltaic/thermal solar collectors are presented in [1738,1739].

Other innovative concepts use polymeric materials of building integrated collectors. Models of collectors with polymer absorbers are presented in [1740,1741]. Burch [1742] uses indices based on temperature, humidity and time to predict damage and weathering of polymeric materials. Analysis of various parameter on performance of transpired solar collectors are presented in [1743–1745].

21.4. Water heating

Innovations in the design of systems for heating water are proposed. Heat pipe water collectors are analyzed by Mathioulakis [1746] and Yang [1747]. Groenhout [1748] proposes a double-sided flat plate absorber mounted on stationary concentrators. Experiments indicate that heat losses are reduced compared to conventional designs. Aye [1749] compares a vapor compression heat pump to other water heating options for application in Australia. A compound parabolic concentrating integral collector storage system is tested by Tripanagnostopoulos et al. [1750]. Rincon [1751] proposes a two-dimensional concentrator for the classic compound parabolic concentrator.

Models of solar water heating include a comparison of high and low efficiency systems [1752], a simplified model of thermosyphon systems [1753] an optimization design tool for large systems [1754], and a TRNSYS model of an indirect thermosyphon system with a mantle heat exchanger. Knudsen [1755] considers the effect of water consumption profile on system performance. Meir [1756] presents a method to predict the solar gain of a large solar water heating system using the storage as a calorimeter.

21.5. Space heating and cooling

Papers address cooling and dehumidification. Grossman [1757] reviews current trends in solar-powered air conditioning. Models or performance of specific absorption cooling and dehumidification systems are presented in [1758–1767]. A Second Law analysis is presented by Izquierdo [1768]. Zhu [1769] investigates methods to reduce the contact resistance between the absorber surface and absorbent. Liu [1770] measured boiling heat transfer in a concentric tube.

21.6. Solar desalination and solar ponds

Papers in this section are restricted to systems that use solar energy. A model of behavior due to radiation transients is presented by Haddad [1771]. Refs. [1772–1774] aim to provide a better understanding of heat and mass transfer in various solar stills. Agha [1775] predicts the ratio of the evaporation pond to that of a salt gradient solar pond in a coupled arrangement. Hermann [1776] tested a collector made of selective surface glass tubes with a reflector to improve performance. Zheng and Ge [1777] tested an active regenerative solar still indoors with a solar simulator and found the performance was 2–3 times greater than a conventional basin-type solar still.

21.7. Storage

Most papers in this section address latent heat storage. Spherical ice storage is investigated in [1778]. Eutectic mixtures of lauric and stearic acids [1779], capric and lauric acids [1780] are evaluated. Phase change materials combined with conductive materials are considered by [1781,1782]. Numerical results indicate that a finned tube latent heat storage models performs better than a tube without fins [1783]. Periodic phase-change of a slab, a process dominated by conduction, is measured by Casano [1784]. Cjibana [1785] tested a water–silicone oil emulsion to make ice.

Sensible heat storage papers for water heating consider natural convection in a vertical cylindrical enclosure [1786], and the use of multiple tank storage units to achieve thermal stratification [1787]. Badescu [1788] models storage combined with a solar heat pump. An exergy analysis of an ammonia synthesis reactor for an ammonia-based thermochemical storage system is presented by Kreetz [1789]. A review of exergy and entropy generation minimization and examples drawn from sensible and latent heat storage are presented by Bejan [1790].

21.8. Water treatment

A simple wood hot box was evaluated as a water disinfecting system by Saitoh [1791]. Work at the University of Florida considered the efficacy of dyes as sensitizing agents for solar photochemical detoxification and calibration of a UV radiometer to measure radiation from black lights used to simulate the solar UV spectrum [1792,1793].

21.9. Solar agricultural applications

Experimental evaluation of a natural convection solar dryer and biomass burner were conducted [1794].

21.10. Buildings

This section includes papers on building integrated solar systems, heat transfer in building components, and glazings.

Coatings for glazing and other window treatments are discussed in numerous papers. Controlling the exhaust flow rate in triple-glazed window systems to reduce the space heat gain was examined in [1795] Naylor [1796] presents flow and temperature visualization of free convection about louvered blind adjacent to an isothermal vertical plate (simulating a window). Thermotropic layers to reduce solar transmittance are measured in [1797]. Optical and thermal properties of granular silica aerogels sandwiched between polymer skins filled with krypton are reported in [1798]. Experiments to determine time and local averaged mixed convection heat transfer coefficients in a vertical transparent channel with horizontal ventilation gratings is presented by Zollner [1799]. An accessory to a spectrophotometer which permits accurate measurement of directional reflectance and transmittance is presented by Van Nihnatten [1800].

Li [1801] uses DOE-2 to illustrate the advantage of daylighting. Scartezzini [1802] tested the use of non-imaging optics to provide diffuse daylighting.

Papers that present modeling results for the building envelope components include an evaluation of roofs with a polystyrene layer [1803], a review of heat transfer through walls with relatively complicated internal structure [1804], ventilation in the ThermoDeck concrete floor system [1805], and a model of transient conduction in structural walls [1806]. A model of heat and mass transfer in whole buildings is presented in [1807]. Simplified methods to model building thermal processes are presented by [1808,1809]. Wen [1810] analyzes the spatial distribution of absorbed solar energy in a room. Temperatures of homes typical of northwestern Mexico are modeled by Porta-Gandara [1811]. Performance of a passive thermal wall in a full scale room is measured in [1812]. Passive ventilation of a one-storey building by a hot element is suggested for removal of toxic gases [1813]. Infrared thermal imaging of thermochromic coatings for building facades are presented in [1814] Building integrated collectors made of concrete slabs [1815] and natural convection water loops that act as thermal diodes are tested.

21.11. High temperature applications

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

A special issue of the ASME *Journal of Solar Energy Engineering* in May 2002 was devoted to solar thermal power. Papers addressed parabolic trough technology, central receivers, and thermochemical reactors and processes.

The current state-of-the-art of parabolic trough solar collector power technology and current R&D efforts are reviewed in [1816,1817]. Recent experimental and modeling efforts as part of the European program aimed at direct steam generation are presented in [1818–1820]. A method to estimate the optimized parabolic trough field size as a function of solar irradiance is presented in [1821] Testing of materials and safety tests of a molten salt thermal storage system for parabolic trough plants are discussed in [1822]. A system that generates steam form compound parabolic concentrators is modeled in [1823].

An update on solar central receiver systems is provided by Romero [1824]. Vant-Hull [1825] gives an overview of molten-salt central receivers and presents design methods to reduce the peak flux to acceptable values in a cost effective manner. Barth et al. [1826] describe a pump for such a system.

Tests of a prototype non-imaging focusing heliostat consisting of a number of grouped slave mirrors are presented in [1827] Measurement techniques for concentrated solar power are presented in [1828–1830] and for dish/Stirling systems in [1831]. Solar brightness profiles obtained from sites in France, Germany, and Spain were compared to measurements taken in the 1970s and a statistical data base was developed for calculating the influence of variable conditions on solar concentrating systems [1832].

Solar hybrid power generation systems investigated include a gas turbine-based tower system [1833], a triple cycle with a high-temperature MHD generator [1834], and hybrid dish/Stirling systems [1835]. Kribus [1836] discusses a micro system on the order of a few Watts for use with solar or fuel-derived heat. Refs. [1837,1838] provide experimental data for a 200 cm diameter fiber optic mini-dish.

Papers on themochemical process cover a variety of topics including methane reformation [1839], reduction of zinc-oxide [1840], and glazing of thermal barrier coatings [1841]. Solar reactor/receiver designs are discussed in [1842,1843].

The use of concentrated solar energy to conduct material testing is discussed and test results for copper alloy intended for the combustion chamber of cryogenic motors are given in [1844].

22. Plasma heat transfer and MHD

22.1. Fundamental investigations

Two publications address the question of transport phenomena in thermal plasmas. An expression for combined diffusion coefficients in a two-temperature plasma has been derived, and it has been demonstrated that the derived expressions for the ambipolar diffusion are consistent with conservation of mass laws [1845]. Using the approach of describing the radiation transport in emitting absorbing plasmas with the method of partial characteristics, values for net emission coefficients have been calculated for cylindrical argon plasmas in the temperature range between 1000 and 30,000 K [1846], thus providing a set of data for solving the energy conservation in such plasmas without the need for solving the radiation transport equation. Three-dimensional descriptions of arcs with super-imposed flows have appeared, both for the description of general arc behavior and for specific applications. Li and Chen [1847] describe the arc in a channel with a constricted anode attachment assuming laminar flow, finding good agreement of their predicted arc voltage and anode attachment position with experimentally observed values. The same authors have extended their model to include the turbulent plasma jet with injection of cold gas and particulates from one side [1848]. A similar model is presented by Ramachandran and Nishiyama [1849]. The plasma induced flow patterns are modeled in a rf glow discharge reactor, and the effect of the applied frequency and discharge voltage on this flow is demonstrated [1850]. Christlieb and Hitchon [1851] present a model for heat transfer in a rarefied plasma between two parallel plates based on a three dimensional solution of the Boltzmann equation.

For using Thomson scattering in atmospheric pressure plasmas for determination of electron temperature and density, a new approach has been developed which results in experimental data that are consistent with those derived from other techniques [1852]. A description of the cathode region of atmospheric pressure arcs is presented by Benilov [1853]. Furukawa et al. [1854] present a description of reduced heat transfer from an arc to a molten copper anode when copper vapor is present. A review of electrode phenomena and their influence on plasma torch design is presented in [1855].

22.2. Specific applications

Plasma investigations continue to address more and more specific applications. Plasma spraying is one application which has been described in a number of models, and some fundamental issues of the process have been investigated experimentally. Modeling of the coating formation process has made amazing advances, as demonstrated by the three dimensional description of the splatting and solidification of liquid metal droplets on uneven surfaces [1856]. A similar model describes the coating formation using a somewhat different approach, with the major unknowns being used as parameters [1857]. Two modeling efforts have been directed at describing the entire spray process, from particle injection to coating formation [1858,1859], and both models aspire to provide a tool for process optimization. The effect of arc instabilities in a plasma spray torch on the coating characteristics are described in [1860], and the instabilities are related to the fluid dynamic boundary layer inside the anode nozzle. A combined experimental and theoretical study has led to the description of evaporation of iron spray particles and the resulting formation of iron oxide fumes [1861]. A similar but purely theoretical approach has been used for the description of the surface oxidation of molybdenum particles and subsequent evaporation of the oxide [1862]. The formation of thermally sprayed silicon nitride layers by using a composite spray powder consisting of silicon nitride particles embedded in a complex binder matrix is described in [1863]. Two publications deal with wire arc spray coating processes, one describes theoretically the formation of spray formed preforms [1864], while the other presents a model of the entire spray process, including the compressible flow model for the supersonic upstream part of the flow, the three dimensional description of the interaction of the arc with the flow, the turbulent flow in the jet, the droplet formation from the anode and from the cathode in two different models, and the droplet trajectories in the turbulent jet [1865].

Three models are described for welding arcs. One of these considers a tungsten inert gas (TIG) welding process and includes in the model the cathode and the molten weld pool, describing the different forces on the liquid metal [1866]. The second one by the same authors concentrates on describing the interaction between the arc and the molten metal anode [1867]. The third one describes details of the anode boundary layer processes and confirms previous observations about the importance of the electron transport associated heat flux [1868]. Electrode processes in high intensity discharge lamps are described by Dabringhausen et al. [1869] in a series of papers highlighting the electrode fall measurements and modeling results. A model based on an LTE description of a microwave driven high pressure sulfur lamp is presented by Johnston et al. [1870], and the heat transfer contributions from conduction and molecular radiation are described. Three publications deal with plasma heat transfer in the three applications of reentry space flight vehicles into the earth atmosphere, microelectronic processing, and acetylene synthesis from methane. For the reentry simulation, an inductively coupled plasma source operated with oxygen and carbon dioxide is described [1871]. The study of an inductively coupled wafer etch reactor demonstrated the effect of ion bombardment on the heat transfer to a wafer [1872]. An improvement of conversion efficiency and yield of an acetylene synthesis reactor could be achieved through changes in the fluid dynamic design of the reactor [1873].

22.3. Magnetohydrodynamics

The effect of a magnetic field on the natural convection heat transfer in a liquid metal is investigated experimentally and numerically, and relations between Nusselt number and Raleigh number are derived [1874]. The same group describes a numerical model of a liquid metal pool during electron beam evaporation, and how the convective heat losses from the crucible can be controlled using external magnetic fields [1875]. In an experimental study of a closed loop thermosyphon arrangement for electrolyte solutions, the Hall parameter for these solutions have been determined [1876]. Another study focuses on the free convection flow in a liquid boron oxide encapsulent layer above a molten semiconductor compound material, and describes the influence of a vertical magnetic field on the convection in the semiconductor liquid [1877]. Two papers deal with three-dimensional simulations of the free convection flows in liquid metal filled cubic enclosures, once with heating on opposite vertical walls [1878], and once with uniform internal heating [1879].

Unsteady MHD flow and heat transfer is simulated for flow over an infinite rotating disk with varying angular velocity, showing the increase in heat transfer with acceleration [1880], and a theoretical solution is obtained for convection along a moving vertical surface with suction [1881]. Mixed convection for flow in a vertical channel with symmetric or asymmetric heating is described by Chamkha [1882]. Another study concerns itself with the unsteady flow of a conductive fluid containing particles between parallel plates with a perpendicular magnetic field, with variations in the viscosity and electrical conductivity [1883]. Another discussion of MHD flow in a porous medium between vertical plates is provided by Singh [1884]. Radiation effects on free convection MHD flow is described by Ghaly [1885], and for unsteady flow with variable viscosity by Seddeek [1886].

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